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MODELING OF OIL REFINING PROCESSES USING GENERALIZED NETS AND INTERCRITERIA ANALYSIS

ABSTRACT
OF A THESIS

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It contains an introduction, 6 chapters and a conclusion in a volume of 150 pages. 239 references are cited. The main results of the dissertation work are presented in 8 scientific publications. 11 citations of 4 of the scientific publications are noted.

The numbers of the figures, tables and equations match those in the dissertation.

The defense of the dissertation will take place on ……….. from ………… in the conference room of the Institute of Biophysics and Biomedical Engineering - Bulgarian Academy of Sciences (105 Acad. G. Bonchev St.).

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Title: Modeling of oil refining processes using generalized nets and intercriteria analysis.

List of abbreviations and symbols used

0.5 S – fuel oil with a sulfur content not higher than 0.5 wt.%;
1.0 S – fuel oil with a sulfur content not higher than 1.0 wt.%;
2.5 S – fuel oil with a sulfur content not higher than 2.5 wt.%;
A-95H – Brand of automotive gasoline with an octane number according to the research method 95;
A-95 B-9 – Brand of automotive gasoline with a research octane number of 95, containing 9% bioethanol;
A-98H – Brand of automotive gasoline with an octane number according to the research method 98;
A-98H B-9 – Brand of automotive gasoline with a research octane number of 98, containing 9% bioethanol;
A-100H = Brand of automotive gasoline with a research octane number of 100;
AR – Atmospheric residue;
BU – road bitumen production plant;
C3C4 = Petroleum fraction of C3 and C4 hydrocarbons;
C4 – A petroleum fraction containing hydrocarbons with a number of carbon atoms in their molecule equal to 4;
C4= A petroleum fraction containing unsaturated hydrocarbons with a number of carbon atoms in their molecule equal to 4;
C5 – A petroleum fraction containing hydrocarbons with a number of carbon atoms in their molecule equal to 5;
CDU – Crude distillation unit;
CGFU – Central gas fractionation unit;
FCC – Fluid catalytic cracking;
FCC PPF Splitter – Rectification column for separation of the propane-propylene fraction into propane and propylene;
FCCPT – Fluid catalytic cracking feed pretreater (hydrotreater);
FCCU – Fluid catalytic cracking unit;
FO – Fuel oil
GN – Generalized net
HAGO – Heavy atmospheric gas oil;
HCKVGO – Hydrocracked vacuum gas oil;
HCO – Heavy cycle oil;
HDS – Hydrodesulphurization unit;
HDS-3 – Hydrotreating plant number 3 of the technological chain of the studied refinery;
HDS-5 – Hydrotreating plant number 5 of the technological chain of the studied refinery;
HPU – Hydrogen production unit;
HTD – Hydrotreated diesel fraction;
HTFCC – Hydrotreated fluid catalytic cracking gasoloine;
HTLSRN – Hydrotreated light straight-run nuphtha;
HTN – Hydrotreated naphtha;
HTVGO – Hydrotreated vacuum gas oil;
H-Oil –ebbulated bed vacuum residue H-Oil hydrocracker;
H-Oil VGO – H-Oil vacuum gas oil;
IDE – Integrated development environment;
Jet A-1 – Aviation fuel;

LCO – Light cycle oil;
LPG – Liquid petroleum gas;
LPG Tank – LPG storage tank;
MTBE – Methyl tertiary butyl ether;
PBFO – Partially blended fuel oil;
PN – Petri net
Prime G – Unit for hydrotreating FCC gasoline using the technology Prime G;
Ref – Catalytic reforming plant;

RMF = Fuel oil;

SLO – FCC slurry oil;
SRHN – Straight-run heavy naphtha;
SRVGO – Straight-run vacuum gas oil;
SRVR – Straight-run vacuum residue;
VDU – Vacuum distillation unit;
VGO – Vacuum gas oil;
VTB – Hydrocracked vacuum residue (vacuum tower bottom product);
GN – Generalized net.

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INTRODUCTION

Petroleum is an energy source that meets 30% of the energy needs of modern humanity and this share is expected to remain unchanged for the next few decades. Its liquid state makes it very convenient for transportation and storage, which is why it is still an indispensable source of energy for our vehicles (cars, buses, trucks, trains, ships and airplanes) that drive the economy of human society. In its original form as mineral oil extracted from the earth's bowels, it is unusable due to the presence of impurities and components harmful to the environment and humans, such as various sulfur, nitrogen and oxygen compounds, as well as organometallic compounds and polycyclic arenes, the removal of which is carried out in oil refineries around the world. Currently, their number is 643, 107 less than their number before 2013. Strong competition, together with constantly growing requirements for reducing emissions of harmful substances, as well as increased requirements for the quality of the fuels produced, requires the oil refining business to find optimal solutions in the presence of a large number of restrictions. Mathematical modeling of the processes of converting oil into final commodity products allows oil refineries to optimize their operations and achieve higher efficiency from both an economic and environmental point of view. Oil refining is essentially a set of parallel processes, in which a wide range of products such as different brands of gasoline, diesel fuels, marine and aviation fuels, fuel oils, road bitumens and others are obtained from a single raw material (crude oil). It has been established that systems in which parallel processes occur can be modeled using the tools of generalized nets, which can be considered as extensions of Petri nets. With the help of generalized nets, processes occurring in biological systems, in various branches of industry, in the economy, in education, in medical care, and others have been modeled. However, generalized nets have not been used to model all processes in the production of different brands of fuels, as well as the entire process of transforming crude oil into final commodity products, encompassing the sub-processes that occur in an oil refinery. Also, to date, no research has been conducted on modeling the entire process of transforming crude oil into final commodity products by jointly using generalized nets and inter-criteria analysis of different types of crude oil, as a tool for selecting a suitable type of crude oil for a given refinery. This led to the formulation of the goal of this dissertation, namely to study the modeling of the production processes of all petroleum products in a modern oil refinery using generalized nets and selection of the crude oil using inter-criteria analysis..

To achieve the set goal, the following tasks have been formulated:

1. To model the production process of different brands of automotive gasoline in an oil refinery using generalized nets;

2. To model the production process of different brands of diesel engine fuels in an oil refinery using generalized nets;

3. To model the production process of different gas fuels, propylene and polypropylene in an oil refinery using generalized nets;

4. To model the production process of different brands of heavy fuel oils and road bitumens in an oil refinery using generalized nets;

5. To model the overall process of transforming crude oil in an oil refinery into final commodity products using generalized nets;

6. To study the relationships between the bulk properties and properties of the fractions of a large number of crude ois and the degree of similarity between them by applying intercriteria analysis.

7. To model the crude oil selection process using intercriteria analysis and the generalized net toolkit.

CHAPTER 1

LITERATURE REVIEW

From the definition of the concept of a generalized net in 1982 to 2025, the use of generalized nets in various research in the fields of medicine and biotechnology; physics and astronomy; computer science; telecommunications, education, industry and others, finds expression in 952 publications, of which 26 monographs, 46 dissertations for the acquisition of the educational and scientific degree "doctor" and one dissertation for the acquisition of the scientific degree "doctor of mathematical sciences" and 879 articles, book chapters and scientific communications presented at conferences. The concept of generalized nets (Gn) appeared as a result of the attempt of Academician Krasimir Atanasov to represent E-nets through transitions with two input and two output places in 1982 and was published two years later, followed by new articles related to the definition of GN. A little later, the time parameters of two extensions of Petri Nets (PNs) - Petri Nets with time (with activation moments) and E-Nets (with duration of active states) posed another problem. Thus, the idea of a new extension of Petri nets was born. It was proven that the functioning and results of the work of the main extensions of Petri nets: E-nets, time-dependent PNs, PRO-nets, colored PNs, regular PNs, predicate/transitional nets, stochastic PNs, generalized E-nets, M-nets, supernets, generalized modification PNs and others are representable by GN. On the other hand, they turned out to be a prerequisite for the emergence of a number of extensions of GN as a tool for modeling parallel processes occurring in large complex systems.

Like other modifications of PNs, GNs have a fixed structure (transitions, places, transition conditions, token characteristics) and dynamic elements - cores. In addition, GNs have time components, such as PN with time, E-nets, PRO-nets and generalized E-nets. However, GNs are the only nets that can be invariant in time. This follows from the introduction of three global time constants in GNs, corresponding to: the initial time moment of net activation - T (to some absolute time scale), the elementary time step of the described process - t_0, the duration of GN functioning. The main advantage is in the absolute time scale, which distinguishes GN from any other type of extensions of PNs. Moreover, any other type of GN with time components has only a part of the time components of GN.

GNs have a fourth distinctive component called "memory". Tokens enter the GN with initial characteristics and acquire new ones through their movement in the net. In this way, they become "individuals" that have their own "history". The idea of the "individualization" of tokens can be seen in a simple form in colored PNs and in predicate/transitional nets. The difference is that GNs can retain all the information accumulated during the functioning of the net. The "memory" component of GN is a source of information about the processes in the net during its functioning.

It has also been shown that GNs are an extension of many other modifications of Petri nets that have emerged since the definition of GNs, such as supernets, fuzzy PNs, etc. This leads to the formulation of the following objectives for GNs:

1. To provide a feasibilitry to compare different types of nets in two senses - as mathematical objects and as tools for modeling parallel processes,

2. To explore the most general properties of GN and transfer them to other nets or more generally - to reality.

Up to the time of the development of this dissertation, there was only one publication dedicated to the use of generalized nets for modeling global processes in an oil refinery [21]. Considering that the study by Dimitrova et al. [21] was conducted 32 years ago and that during this period the studied refinery (Neftochim) was significantly modernized with the addition of new advanced processes and the exclusion of units from the process chain that were economically and environmentally unfavorable, as well as the importance of oil refining as an extremely important sector of the economy of every developed country, it becomes clear that there is a need to conduct research on the modeling of all processes that lead to the conversion of oil into final commodity oil products using generalized nets. This led to the formulation of the goal of this dissertation, namely to study the modeling of the production processes of all petroleum products in a modern oil refinery using generalized nets and selection of the crude oil using intercriteria analysis. With the active participation of the author of this dissertation, 6 articles have been published, which will be discussed in the following chapters.

CHAPTER 2

MODELING OF THE AUTOMOTIVE GASOLINE PRODUCTION PROCESS USING GENERALIZED NETS

The first attempts to apply GN to modeling and simulation of processes in a petrochemical plant were published in [21, 128]. The constructed GN models follow the idea of hierarchical models, extended by unifying or composing simpler ones. The simplified global model describes the general movement of fuels, petroleum products and plastics produced and processed in the plant, taking into account the demand for these goods and the influence of local and global factors (market situation, regulatory acts, price dynamics, etc.).

This chapter uses the capabilities of GN to model the production of various types of automotive gasoline, using the LUKOIL Neftohim Burgas refinery in Bulgaria as an example. Several refining processes run in parallel, producing different components of automotive gasoline: reformate, hydrotreated FCC gasoline (HTFCCG); MTBE (methyl tertiary butyl ether), alkylate, hydrotreated straight-run naphtha, C_5 fraction, isobutane, as well as some other components such as bio-ethanol and imported MTBE (nine components), which are purchased from the market depending on the demand for the types of gasoline and the specifications of the ordered types of gasoline. These parallel processes participate in the overall process of producing different brands of automotive gasoline fuels. The functioning of the constructed GN model is simulated in GN IDE.

The GN model that models the process of producing automotive gasolines contains 21 transitions, 63 places and 13 types of tokens and is shown in Figure 11. The first group of nine toknes are:

α-tokens, which represent hydrotreated FCC gasoline (HTFCC);

β-tokens, which represent reformate;

γ-tokens, which represent alkylate;

δ-tokens, which represent hydrotreated light straight-run naphtha (HTLSRN);

ε-tokens, which represent C_5-fraction;

ζ-tokens, which represent MTBE;

η-tokens, which represent imported MTBE;

θ-tokens, which represent bioethanol;

ι-tokens, which represent isobutane.

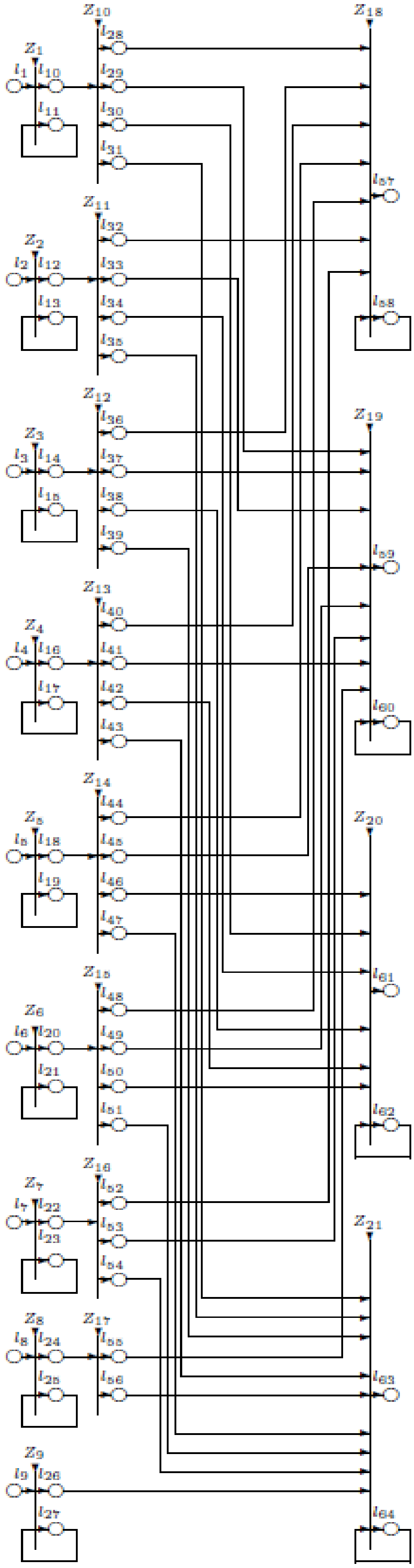

Figure 11. GN model of the production of four brands of automotive gasoline in an oil refinery

These tokens remain permanently in places l_{11}, l_{13}, l_{15}, l_{17}, l_{19}, l_{21}, l_{23}, l_{25}, l_{27}, respectively, with initial and current characteristics:

„current quantity of the respective gasoline component“.

Each of them is divided into two tokens if there is a request for the corresponding raw material, with the original tokens remaining in their places and the new tokens α′, β′, ... get into places l_{10}, l_{12}, l_{14}, l_{16}, l_{18}, l_{20}, l_{22}, l_{24}, l_{26}, respectively, with characteristic

„required quantity of the respective gasoline component“.

The second group with four tokens are:

κ-tokens, which represent A-95H;

λ- tokens, which represent A-95H B9;

μ- tokens, which represent A-98H;

ν- tokens, which represent A-98H B9.

They remain in places permanently l_{58}, l_{60}, l_{62}, l_{64}, respectively, with initial and current characteristics

„current quantity of the respective type of gasoline: A-95H; A-95H B-9; A-98H; A-98H B-9“.

When tokens α, β, ... enter in places l_{58}, l_{60}, l_{62}, l_{64}, they merge with the token, which remains permanently in the corresponding polace, and change the value in its current characteristic.

When there is a need for the appropriate type of gasoline (A-95H; A-95H B-9; A-98H; A-98H B-9 – four grades of gasoline), tokens κ, λ, μ, ν split into two tokensi - the original token and the new token κ′, λ′, ... that enters in place l_{57}, l_{59}, l_{61}, l_{63}, respectively with characteristic

„required quantity of the respective type of gasoline“.

GN transitions have the following forms.

$$Z_1 = \langle \{l_1, l_{11}\}, \{l_{10}, l_{11}\}, r_1 \rangle$$

where,

where,

$W_{11,10}$ = „There is a need for $a_{1,1} + a_{2,1} + a_{3,1} + a_{4,1}$ ton/cubic meter hydrotreated FCC gasoline (HTFCC)“.

$$Z_2 = \langle \{l_2, l_{13}\}, \{l_{12}, l_{13}\}, r_2 \rangle$$

where,

$$r_2 = \begin{array}{c|cc} & l_{12} & l_{13} \\ \hline l_2 & false & true \\ l_{13} & W_{13,12} & true \end{array}$$

where,

$W_{13,12}$ = „There is a need of $a_{1,2} + a_{2,2} + a_{3,2} + a_{4,2}$ ton/cubic meter reformate“.

$$Z_3 = \langle \{l_3, l_{15}\}, \{l_{14}, l_{15}\}, r_3 \rangle$$

where,

$$r_3 = \begin{array}{c|cc} & l_{14} & l_{15} \\ \hline l_3 & false & true \\ l_{15} & W_{15,14} & true \end{array}$$

where

$W_{15,14}$ = „There is a need of $a_{1,3} + a_{2,3} + a_{3,3} + a_{4,3}$ ton/cubic meter alkylate".

$$Z_4 = \langle \{l_4, l_{17}\}, \{l_{16}, l_{17}\}, r_4 \rangle$$

where,

$$r_4 = \begin{array}{c|cc} & l_{16} & l_{17} \\ \hline l_4 & false & true \\ l_{17} & W_{17,16} & true \end{array}$$

where,

$W_{17,16}$ = „There is a need of $a_{1,4} + a_{2,4} + a_{3,4} + a_{4,4}$ ton/cubic meter hidrotreated light straigt-run naphtha (HTLSRN)".

$$Z_5 = \langle \{l_5, l_{19}\}, \{l_{18}, l_{19}\}, r_5 \rangle$$

where,

$$r_5 = \begin{array}{c|cc} & l_{18} & l_{19} \\ \hline l_5 & false & true \\ l_{19} & W_{19,18} & true \end{array}$$

where

$W_{19,18}$ = „There is a need of $a_{1,5} + a_{2,5} + a_{3,5} + a_{4,5}$ ton/cubic meter C_5-fraction".

$$Z_6 = \langle \{l_6, l_{21}\}, \{l_{20}, l_{21}\}, r_6 \rangle$$

where,

$$r_6 = \begin{array}{c|cc} & l_{20} & l_{21} \\ \hline l_6 & false & true \\ l_{21} & W_{21,20} & true \end{array}$$

where,

$W_{21,20}$ = „There is a need of $a_{1,6} + a_{2,6} + a_{3,6} + a_{4,6}$ ton/cubic meter MTBE".

$$Z_7 = \langle \{l_7, l_{23}\}, \{l_{22}, l_{23}\}, r_7 \rangle$$

where,

$$r_7 = \begin{array}{c|cc} & l_{22} & l_{23} \\ \hline l_7 & false & true \\ l_{23} & W_{23,22} & true \end{array}$$

where,

$W_{23,22}$ = „There is a need of $a_{1,7} + a_{2,7} + a_{3,7} + a_{4,7}$ ton/cubic meter imported MTBE".

$$Z_8 = \langle \{l_8, l_{25}\}, \{l_{24}, l_{25}\}, r_8 \rangle$$

where,

$$r_8 = \begin{array}{c|cc} & l_{24} & l_{25} \\ \hline l_8 & false & true \\ l_{25} & W_{25,24} & true \end{array}$$

where

$W_{25,24}$ = „There is a need of $a_{1,8} + a_{2,8} + a_{3,8} + a_{4,8}$ ton/cubic meter bioethanol".

$$Z_9 = \langle \{l_9, l_{27}\}, \{l_{26}, l_{27}\}, r_9 \rangle$$

where,

$$r_9 = \begin{array}{c|cc} & l_{26} & l_{27} \\ \hline l_9 & false & true \\ l_{27} & W_{27,26} & true \end{array}$$

where

$W_{27,26}$ = „There is a need of $a_{1,9} + a_{2,9} + a_{3,9} + a_{4,9}$ ton/cubic meter isobutane".

$$Z_{10} = \langle \{l_{10}\}, \{l_{28}, l_{29}, l_{30}, l_{31}\}, r_{10} \rangle$$

where,

$$r_{10} = \begin{array}{c|cccc} & l_{28} & l_{29} & l_{30} & l_{31} \\ \hline l_{10} & W_{10,28} & W_{10,29} & W_{10,30} & W_{10,31} \end{array}$$

where,

$W_{10,28}$ = „There is a need of $a_{1,1}$ ton/cubic meter HTFCC",

$W_{10,29}$ = „There is a need of $a_{2,1}$ ton/cubic meter HTFCC",

$W_{10,30}$ = „There is a need of $a_{3,1}$ ton/cubic meter HTFCC",

$W_{10,31}$ = „There is a need of $a_{4,1}$ ton/cubic meter HTFCC".

$$Z_{11} = \langle \{l_{12}\}, \{l_{32}, l_{33}, l_{34}, l_{35}\}, r_{11} \rangle$$

where,

$$r_{11} = \begin{array}{c|cccc} & l_{32} & l_{33} & l_{34} & l_{35} \\ \hline l_{12} & W_{12,32} & W_{12,33} & W_{12,34} & W_{12,35} \end{array}$$

where,

$W_{12,32}$ = „There is a need of $a_{1,2}$ ton/cubic meter reformate“,

$W_{12,33}$ = „There is a need of $a_{2,2}$ ton/cubic meter reformate“,

$W_{12,34}$ = „There is a need of $a_{3,2}$ ton/cubic meter reformate“,

$W_{12,35}$ = „There is a need of $a_{4,2}$ ton/cubic meter reformate“.

$$Z_{12} = \langle\{l_{14}\}, \{l_{36}, l_{37}, l_{38}, l_{39}\}, r_{12}\rangle$$

where,

$$r_{12} = \begin{array}{c|cccc} & l_{36} & l_{37} & l_{38} & l_{39} \\ \hline l_{14} & W_{14,36} & W_{14,37} & W_{14,38} & W_{14,39} \end{array}$$

where,

$W_{14,36}$ = „There is a need of $a_{1,3}$ ton/cubic meter alkylate“,

$W_{14,37}$ = „There is a need of $a_{2,3}$ ton/cubic meter alkylate“,

$W_{14,38}$ = „There is a need of $a_{3,3}$ ton/cubic meter alkylate“,

$W_{14,39}$ = „There is a need of $a_{4,3}$ ton/cubic meter alkylate“.

$$Z_{13} = \langle\{l_{16}\}, \{l_{40}, l_{41}, l_{42}, l_{43}\}, r_{13}\rangle$$

where,

$$r_{13} = \begin{array}{c|cccc} & l_{40} & l_{41} & l_{42} & l_{43} \\ \hline l_{16} & W_{16,40} & W_{16,41} & W_{16,42} & W_{16,43} \end{array}$$

where,

$W_{16,40}$ = „There is a need of $a_{1,4}$ ton/cubic meter HTLSRN“,

$W_{16,41}$ = „There is a need of $a_{2,4}$ ton/cubic meter HTLSRN“,

$W_{16,42}$ = „There is a need of $a_{3,4}$ ton/cubic meter HTLSRN“,

$W_{16,43}$ = „There is a need of $a_{4,4}$ ton/cubic meter HTLSRN“.

$$Z_{14} = \langle\{l_{18}\}, \{l_{44}, l_{45}, l_{46}, l_{47}\}, r_{14}\rangle$$

where,

$$r_{14} = \begin{array}{c|cccc} & l_{44} & l_{45} & l_{46} & l_{47} \\ \hline l_{18} & W_{18,44} & W_{18,45} & W_{18,46} & W_{18,47} \end{array}$$

where,

$W_{18,44}$ = „There is a need of $a_{1,5}$ ton/cubic meter C_5-fraction“,

$W_{18,45}$ = „There is a need of $a_{2,5}$ ton/cubic meter C_5-fraction“,

$W_{18,46}$ = „There is a need of $a_{3,5}$ ton/cubic meter C_5-fraction“,

$W_{18,47}$ = „There is a necessity of $a_{4,5}$ ton/cubic meter C_5-fraction“.

$$Z_{15} = \langle \{l_{20}\}, \{l_{48}, l_{49}, l_{50}, l_{51}\}, r_{15} \rangle$$

where,

$$r_{15} = \begin{array}{c|cccc} & l_{48} & l_{49} & l_{50} & l_{51} \\ \hline l_{20} & W_{20,48} & W_{20,49} & W_{20,50} & W_{20,51} \end{array}$$

where,

$W_{20,48}$ = „There is a need of $a_{1,6}$ ton/cubic meter MTBE“,

$W_{20,49}$ = „There is a need of $a_{2,6}$ ton/cubic meter MTBE“,

$W_{20,50}$ = „There is a need of $a_{3,6}$ ton/cubic meter MTBE“,

$W_{20,51}$ = „There is a need of $a_{4,6}$ ton/cubic meter MTBE“.

$$Z_{16} = \langle \{l_{22}\}, \{l_{52}, l_{53}, l_{54}\}, r_{16} \rangle$$

where,

$$r_{16} = \begin{array}{c|ccc} & l_{52} & l_{53} & l_{54} \\ \hline l_{22} & W_{22,52} & W_{22,53} & W_{22,54} \end{array}$$

where,

$W_{22,52}$ = „There is a necessity of import of $a_{1,7}$ ton/cubic meter MTBE“,

$W_{22,53}$ = „There is a necessity of import of $a_{2,7}$ ton/cubic meter MTBE“,

$W_{22,54}$ = „There is a necessity of import of $a_{3,7}$ ton/cubic meter MTBE“.

$$Z_{17} = \langle \{l_{24}\}, \{l_{55}, l_{56}\}, r_{17} \rangle$$

where,

$$r_{17} = \begin{array}{c|cc} & l_{55} & l_{56} \\ \hline l_{24} & W_{24,55} & W_{24,56} \end{array}$$

where,

$W_{24,55}$ = „There is a need of $a_{2,8}$ ton/cubic meter bioethanol“,

$W_{24,56}$ = „There is a need of $a_{4,8}$ ton/cubic meter bioethanol“.

$$Z_{18} = \langle \{l_{26}, l_{28}, l_{32}, l_{36}, l_{40}, l_{44}, l_{48}, l_{52}, l_{58}\}, \{l_{57}, l_{58}\}, r_{18} \rangle$$

where,

$$r_{18} = \begin{array}{c|cc} & l_{57} & l_{58} \\ \hline l_{26} & false & true \\ l_{28} & false & true \\ l_{32} & false & true \\ l_{36} & false & true \\ l_{40} & false & true \\ l_{44} & false & true \\ l_{48} & false & true \\ l_{52} & false & true \\ l_{58} & true & true \end{array}.$$

$$Z_{19} = \langle\{l_{29}, l_{33}, l_{37}, l_{41}, l_{45}, l_{49}, l_{55}, l_{60}\}, \{l_{59}, l_{60}\}, r_{19}\rangle$$

where,

$$r_{19} = \begin{array}{c|cc} & l_{59} & l_{60} \\ \hline l_{29} & false & true \\ l_{33} & false & true \\ l_{37} & false & true \\ l_{41} & false & true \\ l_{45} & false & true \\ l_{49} & false & true \\ l_{55} & false & true \\ l_{60} & true & true \end{array}.$$

$$Z_{20} = \langle\{l_{30}, l_{34}, l_{38}, l_{42}, l_{46}, l_{50}, l_{53}, l_{62}\}, \{l_{61}, l_{62}\}, r_{20}\rangle$$

where,

$$r_{20} = \begin{array}{c|cc} & l_{61} & l_{62} \\ \hline l_{30} & false & true \\ l_{34} & false & true \\ l_{38} & false & true \\ l_{42} & false & true \\ l_{46} & false & true \\ l_{50} & false & true \\ l_{53} & false & true \\ l_{62} & true & true \end{array}.$$

$$Z_{21} = \langle\{l_{31}, l_{35}, l_{39}, l_{43}, l_{47}, l_{51}, l_{54}, l_{56}, l_{64}\}, \{l_{63}, l_{64}\}, r_{21}\rangle$$

where,

$$r_{21} = \begin{array}{c|cc} & l_{63} & l_{64} \\ \hline l_{31} & false & true \\ l_{35} & false & true \\ l_{39} & false & true \\ l_{43} & false & true \\ l_{47} & false & true \\ l_{51} & false & true \\ l_{54} & false & true \\ l_{56} & false & true \\ l_{64} & true & true \end{array}.$$

Publications for Chapter 2

The presented results are included in the article:

160. Stratiev, D.D.; Zoteva, D.; Stratiev, D.S.; Atanassov, K. Modelling the Process of Production of Automotive Gasoline by the Use of Generalized Nets, In Uncertainty and Imprecision in Decision Making and Decision Support: New Advances, Challenges, and Perspectives; Lecture Notes in Networks and Systems; Springer: Cham, Switzerland, 2022; Volume 338.

CHAPTER 3.

MODELING OF THE DIESEL FUEL PRODUCTION PROCESS USING GENERALIZED NETS

The focus of this chapter is on modeling the production of different types of automotive diesel fuels in a petroleum refinery. Two refining processes: hydrotreating of primary and secondary light and heavy middle distillates, together with imported biodiesel, cetane improvers, lubricants and antistatic additives, run in parallel, supplying components for the production of five types of automotive diesel fuels. The imported components for the production of diesel fuel in the petroleum refinery, the subject of this study, are purchased from the market depending on the demand for the types of automotive diesel fuels and the specifications of the ordered diesel fuels.

The production of diesel fuel in a refinery is a typical parallel process, in which some of the components of the diesel fuel are produced by hydrotreating various middle distillate fractions of petroleum, and others are imported, such as biodiesel, cetane improver, lubricity additive, cold flow property improvers such as cloud point, cold filter plugging point and antistatic additive. The GN model contains 19 transitions, 58 places and seven types of tokens, representing the seven brands of diesel fuels produced in the studied petroleum refinery (see Fig. 19).

The first group with seven tokens are:

α-tokens, which are hydrotreated heavy middle distillates with a sulfur content below 10 ppm;

β-tokens, which are a mixture of hydrotreated light and heavy middle distillates with a sulfur content below 10 ppm;

γ-tokens, which are biodiesel;

δ-tokens, which are a cetane improver;

ε-tokens, which are a lubricating additive;

ζ-tokens, which are cold flow imporovers;

η-tokens, which are an antistatic additive.

They remain in places permanently l_9, l_{11}, l_{13}, l_{15}, l_{17}, l_{19}, l_{21}, respectively, with an initial and current characteristic "current quantity of the relevant component of the diesel fuel".

Each of them is divided into two tokenss if there is a request for the corresponding diesel fuel component - the original token and the new token α′, β′, ..., η′, which comes into place l_8, l_{10}, l_{12}, l_{14}, l_{16}, l_{18}, l_{20}, respectively, with the characteristic "required quantity of the relevant component of diesel fuel".

The second group with five tokens are:

κ-tokens, which represent Euro VI diesel fuel for export;

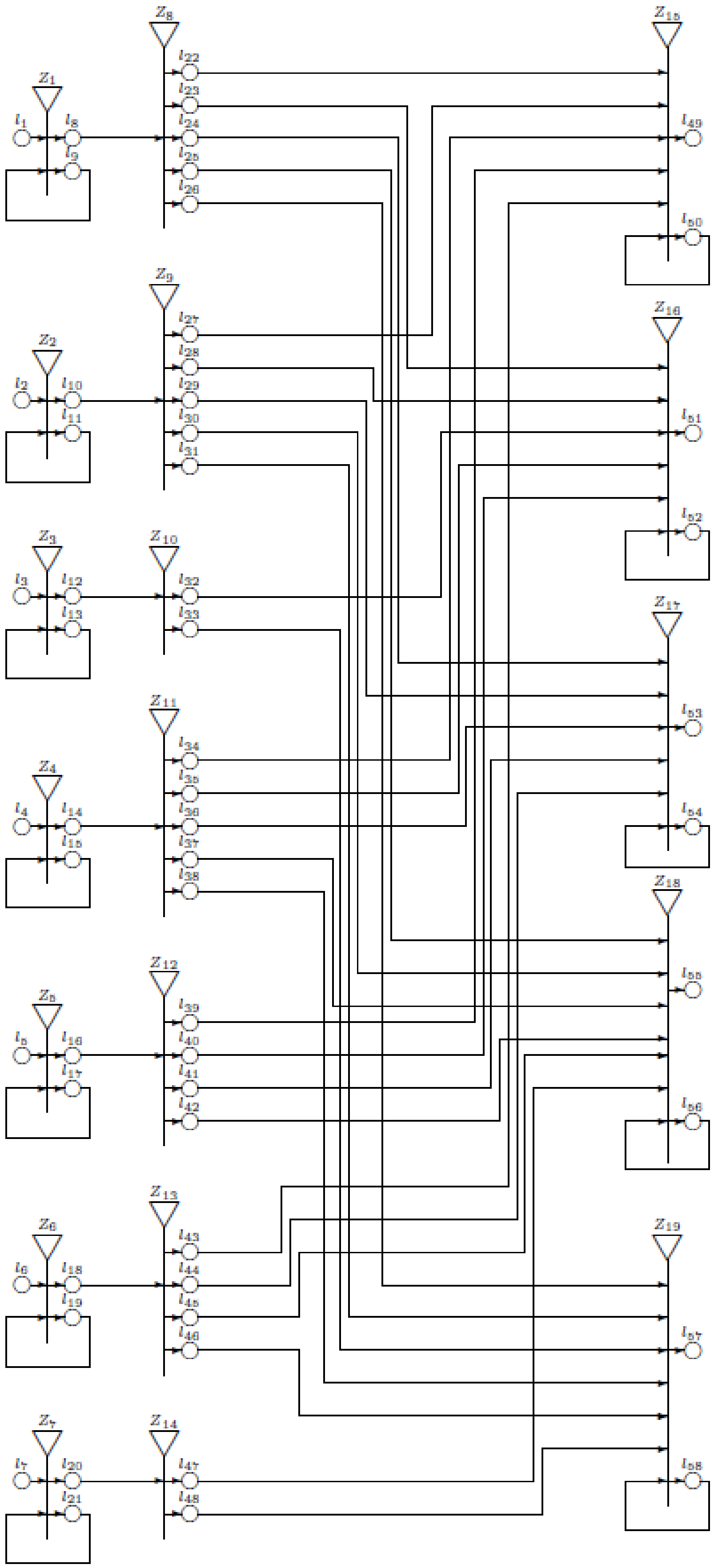

Figure19. GN model of diesel fuel production in the studied oil refinery.

λ-tokens, which are Euro VI diesel fuel containing a biodiesel component;

μ-tokens, which are diesel fuel for off-road vehicles;

ν-tokens, which are Arctic diesel Euro VI;

π-tokens, which are Euro VI Arctic diesel fuel containing a biodiesel component.

They remain in places permanently l_{50}, l_{52}, l_{54}, l_{56}, l_{58}, respectively, with initial and current characteristics

"current quantity of the relevant type (Euro VI diesel for export; Euro VI diesel containing a biodiesel component; off-road diesel; Euro VI Arctic diesel; Euro VI Arctic diesel containing a biodiesel component)".

When α, β, ..., η tokens enter any of the places l_{50}, l_{52}, l_{54}, l_{56}, l_{58}, they merge with the token, which remains permanently in the corresponding place, and change the value in its current characteristic.

When there is a need for the relevant types: Euro VI diesel fuel for export; Euro VI diesel fuel containing a biodiesel component; diesel fuel for off-road vehicles; Euro VI Arctic diesel fuel; Euro VI Arctic diesel fuel containing a biodiesel component (five types), tokenss κ, λ, μ, ν, π are ddivided into two tokes – the original one and the new token κ′, λ′, ..., π′, that enters in places l_{51}, l_{53}, l_{55}, l_{57}, l_{59}, respectively with characteristic

"required quantity of the respective type of diesel fuel".

GN transitions have the following forms.

$$Z_1 = \langle \{l_1, l_9\}, \{l_8, l_9\}, r_1 \rangle$$

where,

$$r_1 = \begin{array}{c|cc} & l_8 & l_9 \\ \hline l_1 & false & true \\ l_9 & W_{9,8} & true \end{array}$$

where,

$W_{9,8}$ =„there is a need of $a_{1,1}$ +$a_{2,1}$ +$a_{3,1}$ +$a_{4,1}$ +$a_{5,1}$ ton/m^3 hydrotreated heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)“.

$$Z_2 = \langle \{l_2, l_{11}\}, \{l_{10}, l_{11}\}, r_2 \rangle$$

where,

$$r_2 = \begin{array}{c|cc} & l_{10} & l_{11} \\ \hline l_2 & false & true \\ l_{11} & W_{11,10} & true \end{array}$$

where,

$W_{11,10}$ = „there is a need of $a_{1,2}$ + $a_{2,2}$ + $a_{3,2}$ + $a_{4,2}$ + $a_{5,2}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)“.

$$Z_3 = \langle \{l_3, l_{13}\}, \{l_{12}, l_{13}\}, r_3 \rangle$$

where,

$$r_3 = \begin{array}{c|cc} & l_{12} & l_{13} \\ \hline l_3 & false & true \\ l_{13} & W_{13,12} & true \end{array}$$

where,

$W_{13,12}$ =„there is a need of $a_{1,3}$ +$a_{2,3}$ +$a_{3,3}$ +$a_{4,3}$ +$a_{5,3}$ ton/m^3 biodiesel".

$$Z_4 = \langle \{l_4, l_{15}\}, \{l_{14}, l_{15}\}, r_4 \rangle$$

where,

$$r_4 = \begin{array}{c|cc} & l_{14} & l_{15} \\ \hline l_4 & false & true \\ l_{15} & W_{15,14} & true \end{array}$$

where,

$W_{15,14}$ = „there is a need of $a_{1,4}$ +$a_{2,4}$ +$a_{3,4}$ +$a_{4,4}$ +$a_{5,4}$ ton/m^3 cetane improver".

$$Z_6 = \langle \{l_6, l_{19}\}, \{l_{18}, l_{19}\}, r_6 \rangle$$

where,

$$r_6 = \begin{array}{c|cc} & l_{18} & l_{19} \\ \hline l_6 & false & true \\ l_{19} & W_{19,18} & true \end{array}$$

where,

$W_{19,18}$ = „there is a need of $a_{1,6}$ + $a_{2,6}$ + $a_{3,6}$ + $a_{4,6}$ + $a_{5,6}$ ton/m^3 cold flow improver".

$$Z_7 = \langle \{l_7, l_{21}\}, \{l_{20}, l_{21}\}, r_7 \rangle$$

where,

$$r_7 = \begin{array}{c|cc} & l_{20} & l_{21} \\ \hline l_7 & false & true \\ l_{21} & W_{21,20} & true \end{array}$$

where,

$W_{21,20}$ = „there is a need of $a_{1,7}$ + $a_{2,7}$ + $a_{3,7}$ + $a_{4,7}$ + $a_{5,7}$ ton/m^3 antistatic additive".

$$Z_8 = \langle \{l_8\}, \{l_{22}, l_{23}, l_{24}, l_{25}, l_{25}\}, r_8 \rangle$$

where,

$$r_8 = \begin{array}{c|ccccc} & l_{22} & l_{23} & l_{24} & l_{25} & l_{26} \\ \hline l_8 & W_{8,22} & W_{8,23} & W_{8,24} & W_{8,25} & W_{8,26} \end{array}$$

where,

$W_{8,22}$ = „there is a need of $a_{1,1}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)",

$W_{8,23}$ = „there is a need of $a_{2,1}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)",

$W_{8,24}$ = „there is a need of $a_{3,1}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)",

$W_{8,25}$ = „there is a need of $a_{4,1}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)",

$W_{8,26}$ = „there is a need of $a_{5,1}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-5)".

$$Z_9 = \langle \{l_{10}\}, \{l_{27}, l_{28}, l_{29}, l_{30}, l_{31}\}, r_9 \rangle$$

where,

$$r_9 = \begin{array}{c|ccccc} & l_{27} & l_{28} & l_{29} & l_{30} & l_{31} \\ \hline l_{10} & W_{10,27} & W_{10,28} & W_{10,29} & W_{10,30} & W_{10,31} \end{array}$$

where,

$W_{10,27}$ = „there is a need of $a_{1,2}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-3)",

$W_{10,28}$ = „there is a need of $a_{2,2}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-3)",

$W_{10,29}$ = „there is a need of $a_{3,2}$ ton/m^3 mixture of hydrotreated light and middle distillates heavy middle distillates with a sulfur content below 10 ppm (diesel fuel from HDS-3)",

$W_{10,30}$ = „there is a need of $a_{4,2}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-3)",

$W_{10,31}$ = „there is a need of $a_{5,2}$ ton/m^3 hydrotreated light and heavy middle distillates with a sulfur level below 10 ppm (diesel fuel from HDS-3)".

$$Z_{10} = \langle \{l_{12}\}, \{l_{32}, l_{33}\}, r_{10} \rangle$$

where,

$$r_{10} = \begin{array}{c|cc} & l_{32} & l_{33} \\ \hline l_{12} & W_{12,32} & W_{12,33} \end{array}$$

where,

$W_{12,32}$ = „there is a need of $a_{1,3}$ ton/m^3 biodiesel",

$W_{12,33}$ = „there is a need of $a_{2,3}$ ton/m^3 biodiesel“.

$$Z_{11} = \langle \{l_{14}\}, \{l_{34}, l_{35}, l_{36}, l_{37}, l_{38}\}, r_{11} \rangle$$

where,

$$r_{11} = \begin{array}{c|ccccc} & l_{34} & l_{35} & l_{36} & l_{37} & l_{38} \\ \hline l_{14} & W_{14,34} & W_{14,35} & W_{14,36} & W_{14,37} & W_{14,38} \end{array}$$

where,

$W_{14,34}$ = „there is a need of $a_{1,4}$ ton/m^3 cetane improver“,

$W_{14,35}$ = „there is a need of $a_{2,4}$ ton/m^3 cetane improver“,

$W_{14.36}$ = „there is a need of $a_{3,4}$ ton/m^3 cetane improver“,

$W_{14.37}$ = „there is a need of $a_{4,4}$ ton/m^3 cetane improver“,

$W_{14.38}$ = „there is a need of $a_{5,4}$ ton/m^3 cetane improver“.

lubricating additive

$$Z_{12} = \langle \{l_{16}\}, \{l_{39}, l_{40}, l_{41}, l_{42}\}, r_{12} \rangle$$

where,

$$r_{12} = \begin{array}{c|cccc} & l_{39} & l_{40} & l_{41} & l_{42} \\ \hline l_{16} & W_{16,39} & W_{16,40} & W_{16,41} & W_{16,42} \end{array}$$

where,

$W_{16,39}$ = „there is a need of $a_{1,5}$ ton/m^3 lubricating additive“,

$W_{16,40}$ = „there is a need of $a_{2,5}$ ton/m^3 lubricating additive“,

$W_{16,41}$ = „there is a need of $a_{3,5}$ ton/m^3 lubricating additive“,

$W_{16,42}$ = „there is a need of $a_{4,5}$ ton/m^3 lubricating additive“.

$$Z_{13} = \langle \{l_{18}\}, \{l_{43}, l_{44}, l_{45}, l_{46}\}, r_{13} \rangle$$

where,

$$r_{13} = \begin{array}{c|cccc} & l_{43} & l_{44} & l_{45} & l_{46} \\ \hline l_{18} & W_{18,43} & W_{18,44} & W_{18,45} & W_{18,46} \end{array}$$

where,

$W_{18,43}$ = „there is a need of $a_{1,6}$ ton/m^3 cold flow improver“,

$W_{18.44}$ = „there is a need of $a_{2,6}$ ton/m^3 cold flow improver“,

$W_{18.45}$ = „there is a need of $a_{3,6}$ ton/m^3 cold flow improver“,

$W_{18.46}$ = „there is a need of $a_{4,6}$ ton/m^3 cold flow improver“.

$$Z_{14} = \langle \{l_{20}\}, \{l_{47}, l_{48}\}, r_{14} \rangle$$

where,

$$r_{14} = \begin{array}{c|cc} & l_{47} & l_{48} \\ \hline l_{20} & W_{20,47} & W_{20,48} \end{array}$$

where,

$W_{20,47}$ = „there is a need of $a_{2,8}$ ton/m^3 cold antistatic additive“,

$W_{20.48}$ = „there is a need of $a_{4,8}$ ton/m^3 cold antistatic additive“.

$$Z_{15} = \langle \{l_{22}, l_{27}, l_{34}, l_{39}, l_{47}, l_{50}\}, \{l_{49}, l_{50}\}, r_{15} \rangle$$

where,

$$r_{15} = \begin{array}{c|cc} & l_{49} & l_{50} \\ \hline l_{22} & false & true \\ l_{27} & false & true \\ l_{34} & false & true \\ l_{39} & false & true \\ l_{47} & false & true \\ l_{50} & true & true \end{array}.$$

$$Z_{16} = \langle \{l_{23}, l_{28}, l_{32}, l_{35}, l_{40}, l_{52}\}, \{l_{51}, l_{52}\}, r_{16} \rangle$$

where,

$$r_{16} = \begin{array}{c|cc} & l_{51} & l_{52} \\ \hline l_{23} & false & true \\ l_{28} & false & true \\ l_{32} & false & true \\ l_{35} & false & true \\ l_{40} & false & true \\ l_{52} & true & true \end{array}.$$

$$Z_{17} = \langle \{l_{24}, l_{29}, l_{36}, l_{41}, l_{44}, l_{56}\}, \{l_{55}, l_{56}\}, r_{17} \rangle$$

where,

$$r_{17} = \begin{array}{c|cc} & l_{55} & l_{56} \\ \hline l_{24} & false & true \\ l_{29} & false & true \\ l_{36} & false & true \\ l_{41} & false & true \\ l_{44} & false & true \\ l_{56} & true & true \end{array}.$$

$$Z_{18} = \langle \{l_{25}, l_{30}, l_{37}, l_{41}, l_{45}, l_{47}, l_{56}\}, \{l_{55}, l_{56}\}, r_{18} \rangle$$

where,

$$r_{18} = \begin{array}{c|cc} & l_{55} & l_{56} \\ \hline l_{25} & false & true \\ l_{30} & false & true \\ l_{37} & false & true \\ l_{41} & false & true \\ l_{45} & false & true \\ l_{47} & false & true \\ l_{56} & true & true \end{array}$$

$$Z_{19} = \langle \{l_{26}, l_{31}, l_{33}, l_{38}, l_{46}, l_{48}, l_{58}\}, \{l_{57}, l_{58}\}, r_{19} \rangle$$

where,

$$r_{19} = \begin{array}{c|cc} & l_{57} & l_{58} \\ \hline l_{26} & false & true \\ l_{31} & false & true \\ l_{33} & false & true \\ l_{38} & false & true \\ l_{46} & false & true \\ l_{48} & false & true \\ l_{58} & true & true \end{array}.$$

Each step of the modeled process can be evaluated through intuitionistic fuzzy pairs (IFP, see [161, 162]). Each IFP has the form ⟨a, в⟩, where a, b, $a + b$ Є [0, 1]. For this we can use information from flow meters placed at the tank outlets (here there are seven of them) for the components of diesel fuel (places l_9, l_{11}, . . . , l_{21} and from flow meters placed at the tank inlets (here the number is five) for storing different brands of diesel fuel (places l_{22}, l_{23}, . . ., l_{48}). For some of the diesel fuel component tanks, the flow meter shows that after the diesel fuel component is depleted, the tank that contains C units remains A units, and the flow meter reading the diesel fuel that enters the finished diesel fuel storage tank shows that B units have entered this tank. Then the intuitionistic fuzzy estimate will have the form $\langle \frac{A}{C}, \frac{B}{C} \rangle$. Obviously, this estimate has the form of IFP, since $\frac{A}{C}, \frac{B}{C}, \frac{A+B}{C} \in [0.1]$. Number $1 - \frac{A}{C} - \frac{B}{C} = \frac{C-A-B}{C}$ corresponds to the amount of diesel fuel component remaining in the pipelines connecting the diesel fuel component tank to the finished diesel fuel tank of the corresponding brand.

The present GN model describes the processes of production of various types of diesel fuels in an oil refinery. It can be used for synchronization and optimization of these processes in a real process control and automation system.

Publications for Chapter 3

The presented results are included in the article:

200. Stratiev, D.D.; Stratiev, D.; Atanassov, K. Modelling the Process of Production of Diesel Fuels by the Use of Generalized Nets. Mathematics 2021, 9, 2351.

CHAPTER 4

MODELING OF THE PRODUCTION PROCESS OF FUEL GAS, PROPANE-BUTANE, PROPYLENE AND POLYPROPYLENE USING GENERALIZED NETS

In this chapter, the focus is on the modeling of the production of fuel gas, liquefied petroleum gas (LPG) or also called propane-butane, propylene and polypropylene, which are part of the hydrocarbon gas refinery production chain, as a complement to the process modeling of the production of automotive gasoline and diesel fuels in the oil refinery using generalized nets. The aim of this chapter is to investigate the process of production of hydrocarbon gas products: fuel gas, LPG and propylene, produced from propylene polypropylene in the oil refinery, and to model it using GN.

The GN model (see Figure 21) contains 17 transitions, 55 places and 47 tokens, which correspond to the following raw materials, products and processing units::

σ_1— crude oil processed into CDU-1, t/h

σ_2— crude oil processed into CDU-2, t/h

σ_3— heavy low-octane gasoline from primary distillation of petroleum, processed in catalytic reforming, t/h

σ_4— fractions of low-octane gasoline and diesel processed in hydrotreating plants, t/h

σ_5— vacuum gas oil processed in a hydrotreater for catalytic cracking feedstock, t/h

σ_6— vacuum residues processed in hydrocracking H-Oil, t/h

σ_7— butane-butylene fraction and isobutene processed in the sulfuric acid alkylation plant, t/h

σ_8— propane-propylene fraction from catalytic cracking, separated in propane and propylene splitter, t/h

σ_9— primary and secondary diesel for hydrotreating in HDS-5 unit, t/h

σ_{10}— hydrotreated vacuum gas oil from H-Oil for processing in catalytic cracking, t/h

σ_{11}— imported natural gas to replenish fuel gas during high fuel gas demand, t/h

ρ_1—crude distillation unit 2 (CDU-2)

ρ_2— crude distillation unit 1 (CDU-1)

ρ_3— catalytic reforming

ρ_4— hydrotreating plants for low octane gasoline and diesel

ρ_5— hydrotreating plant for catalytic cracking feedstock

ρ_6— hydrocracking of vacuum residues H-Oil

ρ_7— sulfuric acid alkylation plant

ρ_8— propane-propylene separation unit (FCC PPF splitter)

ρ_9— gas absorption fractionation unit (AGFU)

ρ_{10}— intermediate LPG tank for collecting raw materials for the central gas fractionation plant

ρ_{11}— diesel hydrotreating plant HDS-5

ρ_{12}— fluid catalytic cracking unit (FCC)

ρ_{13}— central gas fractionation unit (CGFU)

ρ_{14}— liquefied petroleum gas tank farm (LPG)

ρ_{15}— fuel gas tank farm

α_1—LPG product from CDU-2, t/h

α_2—LPG product from CDU-1, t/h

α_3— LPG product from the catalytic reforming of heavy low-octane gasoline, t/h

α_4—LPG product from AGFU, t/h

α_5—feeds for CGFU, t/h

α_6—LPG product from CGFU for filling the tank farm for LPG, t/h

β— fuel gas for AGFU, t/h

β_1— fuel gas product from CDU-2, t/h

β_2— fuel gas product from CDU-1, t/h

β_3— fuel gas product from the catalytic reforming of heavy low-octane gasoline, t/h

β_4— fuel gas product from hydrotreating plants of low octane gasoline and diesel, t/h

β_5— product fuel gas from the FCC feed hydrotreating hydrotreating plant, t/h

β_6— product fuel gas from the hydrocracking of vacuum residues H-Oil, t/h

β_7— propane fraction from the sulfuric acid alkylation plant, t/h

β_8— dry fuel gas from AGFU, t/h

β_9— dry fuel gas from CGFU, t/h

β_{10}— dry fuel gas from HDS-5 unit, t/h

β_{11}— dry fuel gas from FCCU, t/h

γ_1— propane product from FCC PPF splitter, t/h

γ_2— propylene product from FCC PPF splitter to feed the polypropylene plant, t/h

γ_3— propylene product from FCC PPF splitter, t/h

δ_1— high melting point polypropylene product, grade 61, t/h

δ_2— high melting point polypropylene product, grade 63, t/h

δ_3— high melting point polypropylene product, grade 65, t/h

δ_4— high melting point polypropylene product, grade 66, t/h

δ_5— high melting point polypropylene product, grade 65 BOPP, t/h

ε_1—LPG product for export, t/h

ε_2— fuel gas product to power the refinery's power plant, t/h

ε_3— fuel gas product for feeding refinery furnaces, t/h

$$Z_1 = \langle \{l_1, l_{11}\}, \{l_9, l_{10}, l_{11}\}, \begin{array}{c|ccc} & l_9 & l_{10} & l_{11} \\ \hline l_1 & false & false & true \\ l_{11} & W_{11,9} & W_{11,10} & true \end{array} \rangle,$$

where,

$W_{11,9}$ = „there is a request for LPG product from CDU-2“;

$W_{11,10}$ = „there is a request for LPG product from CDU-2“.

Token σ_1 enters place l_{11} and merges with the token ρ_1, to obtain the characteristic: "current amount of crude oil in CDU-2".

At the next time point the token ρ_1 divides into three tokens – same token ρ_1, which continues to stand in place l_{11}, α_1 and β_1.

Token α_1 obtains a characteristic:

„current amount of LPG product from CDU-2“

In place l_9, token β_1 gets a characteristic:

„current quantity of fuel gas product from CDU-2 “in place l_{10}, token ρ_1 gets a characteristic:

„current amount of crude oil in CDU-2“ .

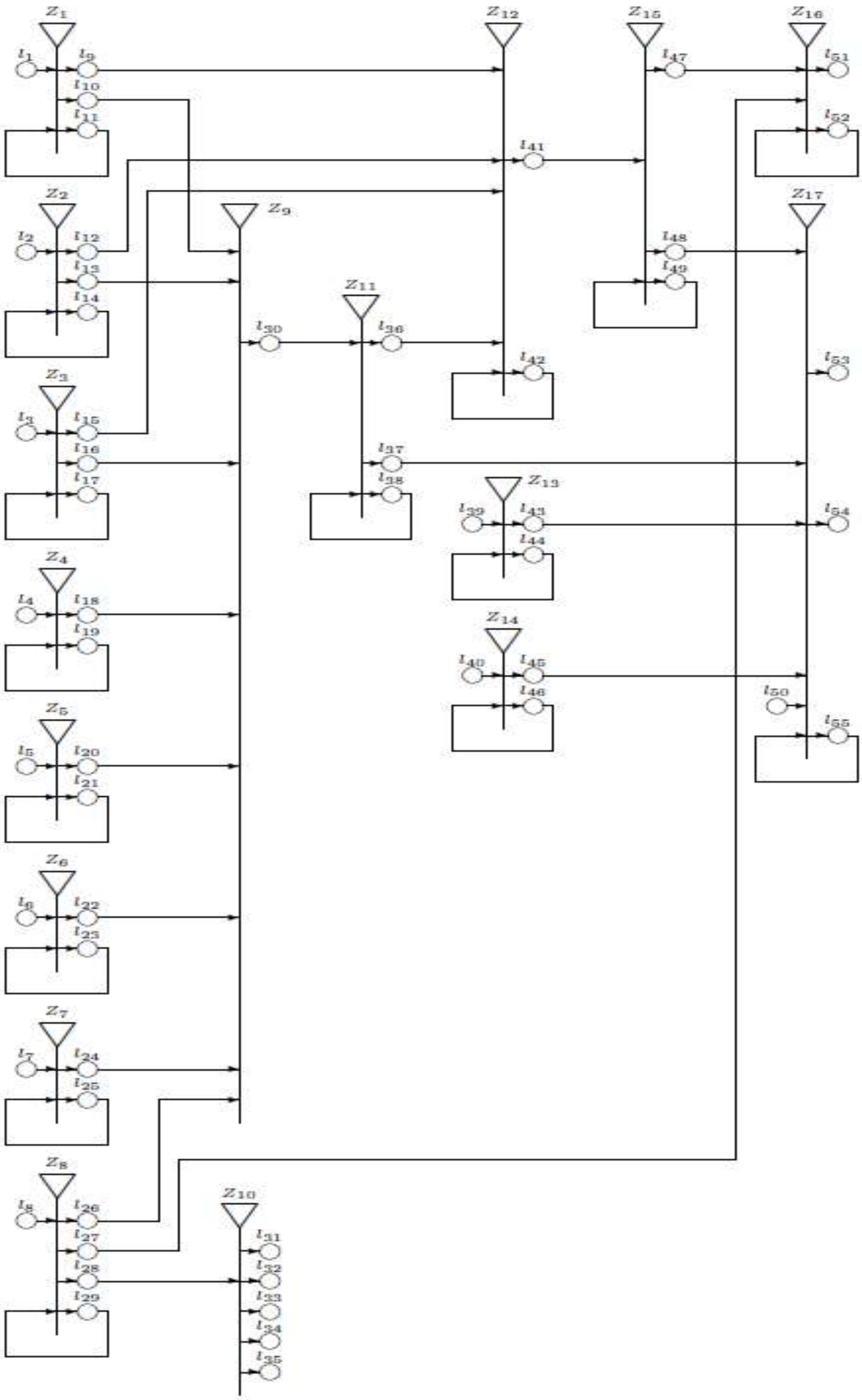

Figure 21. GN model of fuel gas, LPG, propylene and polypropylene production in the oil refinery.

$$Z_2 = \langle \{l_2, l_{14}\}, \{l_{12}, l_{13}, l_{14}\}, \begin{array}{c|ccc} & l_{12} & l_{13} & l_{14} \\ \hline l_2 & false & false & true \\ l_{14} & W_{14,12} & W_{14,13} & true \end{array} \rangle,$$

where,

$W_{14,12}$ = „there is a request for LPG product from CDU-1“;

$W_{14,13}$ = „there is a request for product fuel gas from CDU-1“.

Token σ_2 enters place l_{14} and merges with the token ρ_2, to get the characteristic:

„current amount of crude oil in CDU-1“ .

At the next time point, the token ρ_2 divides into three tokens the same token ρ_2, which continues to stand in place l_{14}, α_2 and β_2.

Token α_2 gets a characteristic:

„current amount of LPG from CDU-1“

In place l_{12}, token β_2 gets a characteristic:

„current amount of fuel gas product from CDU-1“

In place l_{13}, token ρ_2 gets a characteristic:

„current amount of crude oil“

$$Z_3 = \langle \{l_3, l_{17}\}, \{l_{15}, l_{16}, l_{17}\}, \begin{array}{c|ccc} & l_{15} & l_{16} & l_{17} \\ \hline l_3 & false & false & true \\ l_{17} & W_{17,15} & W_{17,16} & true \end{array} \rangle,$$

where,

$W_{17,15}$ = „there is a request for an LPG product from catalytic reforming of low octane gasoline“;

$W_{17,16}$ = „there is a request for a fuel gas product from catalytic reforming of low octane gasoline“.

Token σ_3 comes in place l_{17} and merges with ρ_3 to get a characteristic:

„current amount of low octane gasoline in catalytic reforming“

At the next time point the token ρ_3 divides into thre tokens – same token ρ_3, which continues to stand in place l_{17}, α_3 and β_3.

Token α_3 gets a characteristic:

„ current amount of LPG product from catalytic reforming“

In place l_{15}, token β_3 gets a characteristic:

„current amount of fuel gas from catalytic reforming“

In place l_{16}, token ρ_3 gets a characteristic:

„current amount of fuel gas from catalytic reforming“

$$Z_4 = \langle \{l_4, l_{19}\}, \{l_{18}, l_{19}\}, \begin{array}{c|cc} & l_{18} & l_{19} \\ \hline l_4 & false & true \\ l_{19} & W_{19,18} & true \end{array} \rangle,$$

where,

$W_{19,18}$ = „there is a request for fuel gas from hydrotreating units for low-octane gasoline and diesel“.

Token σ_4 enters into place l_{19} and merges with token ρ_4 to get a characteristic:

„current amount of low octane gasoline and diesel in hydrotreating plants“

At the next time point the token ρ_4 divides into two tokensi – same token ρ_4, which continues to stand in places l_{19} and β_4.

Token β_4 gets a characteristic:

„current amount of fuel gas from hydrotreating plants for low octane gasoline and diesel“.

In place l_{18}, token ρ_4 gets a characteristic:

„current quantity of low octane gasoline and diesel for hydrotreating units for low octane gasoline and diesel“.

$$Z_5 = \langle \{l_5, l_{21}\}, \{l_{20}, l_{21}\}, \begin{array}{c|cc} & l_{20} & l_{21} \\ \hline l_5 & false & true \\ l_{21} & W_{21,20} & true \end{array} \rangle,$$

where,

$W_{21,20}$ = „there is a request for a fuel gas product from a hydrotreating plant of the catalytic cracking feedstock“.

Token σ_5 enters into place l_{21} and merges with token ρ_5 to get the characteristic:

„current amount of vacuum gas oil in the hydrotreating plant for catalytic cracking feedstock“.

At the next time point the token ρ_5 divides into three tokens – same token ρ_5, which continues to stand in places l_{21} and β_5.

Token β_5 gets a characteristic:

„current quantity of product – fuel gas from the hydrotreating plant for catalytic cracking feedstock“.

In place l_{20}, token ρ_5 gets a characteristic:

„current amount of vacuum gas oil in the hydrotreating plant for catalytic cracking feedstock“.

$$Z_6 = \langle \{l_6, l_{23}\}, \{l_{22}, l_{23}\}, \begin{array}{c|cc} & l_{22} & l_{23} \\ \hline l_6 & false & true \\ l_{23} & W_{23,22} & true \end{array} \rangle,$$

where,

$W_{23,22}$ = „there is a request for a fuel gas product from the H-Oil vacuum residue Hydrocracking unit ”

Token σ_6 enters into place l_{23} and merges with token ρ_6 to get the characteristic:

„current amount of vacuum residue in the H-Oil Hydrocracking unit ”.

At the next time point the token ρ_6 divides into two tokens – same token ρ_6, which continues to stand in place l_{23} and β_6.

Token β_6 gets a characteristic:

„current amount of product gas from the H-Oil Hydrocracking unit”

In place l_{22}, token ρ_6 gets a characteristic:

„current amount of vacuum residue in the H-Oil Hydrocracking unit””

$$Z_7 = \langle \{l_7, l_{25}\}, \{l_{24}, l_{25}\}, \begin{array}{c|cc} & l_{24} & l_{25} \\ \hline l_7 & false & true \\ l_{25} & W_{25,24} & true \end{array} \rangle,$$

where,

$W_{25,24}$ = „ there is a request for a product from the propane fraction from the installation Sulfuric acid alkylation“.

Token σ_7 enters in place l_{25} and merges with token ρ_7 to get the characteristic:

„current quantity of butane-butylene fraction and iso-butane in the installation «Sulfuric acid alkylation»“.

Token β_7 gets a characteristic:

„current quantity of propane fraction-product from the installation «Sulfuric acid alkylation»“.

In place l_{24}, token ρ_7 gets a characteristic:

„current quantity of butane-butylene fraction and iso-butane in the installation «Sulfuric acid alkylation»“.

$$Z_8 = \langle \{l_8, l_{29}\}, \{l_{26}, l_{27}, l_{28}, l_{29}\}, \begin{array}{c|cccc} & l_{26} & l_{27} & l_{28} & l_{29} \\ \hline l_8 & false & true & & \\ l_{29} & W_{29,26} & W_{29,27} & W_{29,28} & true \end{array} \rangle,$$

where,

$W_{29,26}$ = „ there is a request for a product propane from FCC PPF splitter for LPG production“;

$W_{29,27}$ = „ there is a request for propylene for polymerization from FCC PPF splitter“;

$W_{29,28}$ = „ there is a request for propylene product from FCC PPF splitter for export “.

Token σ_8 enters into place l_{29} and meges with token ρ_8 to gets the characteristic:

„current amount of FCC PPF in FCC PPF splitter“.

At the next time point the token ρ_8 divides into four tokens – same token ρ_8, which continues to stand in place l_{29} and tokens γ_1, γ_2 and γ_3.

Tokens γ_1, γ_2 and γ_3 get characteristics:

„current amount of propane product in FCC PPF splitter “.

In place l_{26},

„current amount of propylene product for propylene polymerization in FCC PPF splitter “.

In place l_{27},

„current amount of propylene product for export from FCC PPF splitter “.

In place l_{28}. The token ρ_8 gets a characteristic:

„current amount of FCC PPF in FCC PPF splitter “.

$$Z_9 = \langle \{l_{10}, l_{13}, l_{16}, l_{18}, l_{20}, l_{22}, l_{24}, l_{28}\}, \{l_{30}\}, \begin{array}{c|c} & l_{30} \\ \hline l_{10} & true \\ l_{13} & true \\ l_{16} & true \\ l_{18} & true \\ l_{20} & true \\ l_{22} & true \\ l_{24} & true \\ l_{28} & true \end{array} \rangle.$$

All β nuclei unite in place l_{30} with the token β with a charactersitics:

„current amount of fuel gas, feed for AGFU ”

$$Z_{10} = \langle \{l_{28}\}, \{l_{31}, l_{32}, l_{33}, l_{34}, l_{35}\}, \begin{array}{c|ccccc} & l_{31} & l_{32} & l_{33} & l_{34} & l_{35} \\ \hline l_{28} & W_{28,31} & W_{28,32} & W_{28,33} & W_{28,34} & W_{28,35} \end{array} \rangle,$$

where,

$W_{27,31}$ = „there is a request for a polypropylene product with a high melt index grade 61 from the polypropylene plant”;

$W_{27,32}$ = „there is a request for a polypropylene product with a high melt index class 63 from the polypropylene plant ”;

$W_{27,33}$ = „there is a request for a polypropylene product with a high melt index grade 65 from the polypropylene plant ”;

$W_{27,34}$ = „there is a request for a polypropylene product with a high melt index grade 66 from the polypropylene plant ”;

$W_{27,35}$ = „there is a request for a polypropylene product with a high melt index class 66 BOPP from the polypropylene plant ”.

Token γ_2 divides into five tokens $\delta_1,\ldots, \delta_5$, which accordingly receive characteristics:

„current quantity of polypropylene product with high melt index grade 61 in the polypropylene plant“

in place l_{31},

„current quantity of polypropylene product with high melt index grade 63 in the polypropylene plant".

in place l_{32},

„current quantity of polypropylene product with high melt index grade 65 in the polypropylene plant".

in place l_{33},

„current quantity of polypropylene product with high melt index grade 66 in the polypropylene plant"

In place l_{34},

„current quantity of high melt index polypropylene product grade 65 BOPP in the polypropylene plant"

in place l_{35}.

$$Z_{11} = \langle \{l_{30}, l_{38}\}, \{l_{36}, l_{37}, l_{38}\}, \begin{array}{c|ccc} & l_{36} & l_{37} & l_{38} \\ \hline l_{30} & false & false & true \\ l_{38} & W_{38,36} & W_{36,37} & true \end{array} \rangle,$$

where,

$W_{38,36}$ = „there is a request for LPG product from AGFU";

$W_{38,37}$ = „there is a request for a fuel gas product from AGFU".

Token β enters into place l_{38} and merges with token ρ_9 to get the characteristic:

„current amount of fuel gas, feed for AGFU"

At the next time point the token ρ_9 divides into three tokens – same token ρ_9, which continues to stand in placel_{38}, α_4 and β_8.

Token α_4 gets a charatceristic:

„current quantity of LPG product from AGFU"

In place l_{36}, token β_8 gets a charatceristic:

„current amount of fuel gas, feed for AGFU"

In place l_{37}.

$$Z_{12} = \langle \{l_9, l_{12}, l_{15}, l_{36}, l_{42}\}, \{l_{41}, l_{42}\}, \begin{array}{c|cc} & l_{41} & l_{41} \\ \hline l_9 & false & true \\ l_{12} & false & true \\ l_{15} & false & true \\ l_{36} & false & true \\ l_{42} & true & true \end{array} \rangle.$$

All α – tokens (α_1, α_2, α_3, α_4) merges in place l_{42} with token ρ_{10} and its gets a characteristic:

„current quantity of LPG feedstock for CGFU stored in tank farm“

At the next time point the token ρ_{10} divides into two tokens – same token ρ_{10}, which continues to stand in place l_{42}, and token α_5, that enters into place l_{41} with a characteristic:

„current quantity of LPG – feed for CGFU“

$$Z_{13} = \langle \{l_{39}, l_{44}\}, \{l_{43}, l_{44}\}, \begin{array}{c|cc} & l_{43} & l_{44} \\ \hline l_{39} & false & true \\ l_{44} & W_{44,43} & true \end{array} \rangle,$$

where,

$W_{44,43}$ = „there is a request for a fuel gas product from the HDS-5 unit“.

Token σ_9 enters into place l_{44} and merges with token ρ_{11} which receives a characteristic:

„current quantity of diesel fractions of primary and secondary origin used as feedstock for HDS-5 unit“

At the next time point the ntoken ρ_{11} divides into two tokens – same token ρ_{11}, which continues to stand in place l_{44} with a characteristic:

„current quantity of diesel fractions of primary and secondary origin used as feedstock for HDS-5 unit“

And token β_{10}, that enters in place l_{43} with a characteristic:

„current quantity of fuel gas, product of HDS-5 unit“.

$$Z_{14} = \langle \{l_{40}, l_{46}\}, \{l_{45}, l_{46}\}, \begin{array}{c|cc} & l_{45} & l_{46} \\ \hline l_{40} & false & true \\ l_{46} & W_{46,45} & true \end{array} \rangle,$$

where,

$W_{46,45}$ = „there is a request for fuel gas product from FCCU“.

Token σ_{10} enters in place l_{46} and merges with token ρ_{12} to get a characteristic:

„current amount of hydrotreated vacuum gas oil, feed for FCCU“.

At the next time point, the token ρ_{12} divides into two tokens – same token ρ_{12}, which continues to stand in place l_{46} with a characteristic:

„current amount of hydrotreated vacuum gas oil, feedstock for FCCU“

And token β_{11} enters in place l_{45} with a characteristic:

„current quantity of fuel gas – product from FCCU“.

$$Z_{15} = \langle \{l_{41}, l_{49}\}, \{l_{47}, l_{48}, l_{49}\}, \begin{array}{c|ccc} & l_{47} & l_{48} & l_{49} \\ \hline l_{41} & false & false & true \\ l_{49} & W_{49,47} & W_{49,48} & true \end{array} \rangle,$$

where,

$W_{49,47}$ = „there is a request for LPG product from CGFU“;

$W_{49,48}$ = „there is a request for a fuel gas product from CGFU“.

Token α_5 enters in place l_{49} and merges with token ρ_{13} which receives a characteristic:

„current quantity of LPG – feedstock for CGFU“.

in place l_{47}, token β_9 gets a characteriscic:

„current quantity of fuel gas – product of CGFU“

in place l_{48}.

$$Z_{16} = \langle \{l_{26}, l_{47}, l_{52}\}, \{l_{51}, l_{52}\}, \begin{array}{c|cc} & l_{51} & l_{52} \\ \hline l_{26} & false & true \\ l_{47} & false & true \\ l_{46} & true & true \end{array} \rangle.$$

Tokens α_6 and γ_2 enter into l_{52} and merge with token which receives a characteristic:

„current quantity of LPG – product stored in the tank farm for export“.

At the next time point the token ρ_{14} divides into two tokens – same token ρ_{14}, which continues to stand in place l_{51} with a characteristic:

„current quantity of LPG – product sent for export“.

$$Z_{17} = \langle \{l_{37}, l_{43}, l_{45}, l_{48}, l_{50}, l_{55}\}, \{l_{53}, l_{54}, l_{55}\}, \begin{array}{c|ccc} & l_{53} & l_{54} & l_{55} \\ \hline l_{37} & false & false & true \\ l_{43} & false & false & true \\ l_{45} & false & false & true \\ l_{48} & false & false & true \\ l_{50} & false & false & true \\ l_{55} & W_{55,53} & W_{55,54} & false \end{array} \rangle,$$

where,

$W_{55,53}$ = „there is a request for a fuel gas product for the refinery power plant“;

$W_{55,54}$ = „there is a request for a fuel gas product for the refinery's process furnaces“.

Tokens β_8, β_9, σ_9, σ_{10}, σ_{11} enter in place l_{55} and merge with the toiken ρ_{15} which receives a characteristic:

„current amount of fuel gas“.

Token ρ_{15} divides into three – the same token ρ_{15}, which continues to stand in position l_{55} tokens ε_2 and ε_3.

Token ε_2 gets a characteristic:

„current quantity of fuel gas – product for the refinery power plant“

in place l_{53}, token ε_3 gets a characteristic

„current amount of fuel gas for the refinery's process furnaces“

in place l_{54}.

The process of producing gaseous products in an oil refinery, such as fuel gas, propane-butane, and propylene, which can be exported as a final product or used as a raw material for the production of polypropylene, is a complex parallel process that is difficult to model using linear and even dynamic programming. The difficulty comes from the inability to reflect the logic of cause-and-effect relationships in it, which, as mentioned above, are easily interpreted by the predicates of the transition condition. A visual means of representing real processes are UML diagrams, which in [201] are shown as represented by GN.

Publications for Chapter 4

The presented results are included in the article:

202. Stratiev, D.D.; Dimitriev, A.; Stratiev, D.; Atanassov, K. Modeling the Production Process of Fuel Gas, LPG, Propylene, and Polypropylene in a Petroleum Refinery Using Generalized Nets. Mathematics 2023, 11, 3800.

CHAPTER 5

GENERALIZED NET MODEL OF HEAVY OIL PRODUCTION IN AN OIL REFINERY

This chapter focuses on modeling the heavy oil product production process in an oil refinery using the GN toolkit. Five process plants producing ten heavy oil products in an amount of 106.5 t/h from 443 t/h of feedstock, representing atmospheric oil residue, their mixing, pipelines and tank farm intended for storage of finished products consisting of three types of fuel oil (very low sulfur fuel (0.5%S) — 3.4 t/h; low sulfur fuel (1.0%S) — 4.2 t/h; and high sulfur fuel (2.5%S) — 66.9 t/h), and two types of road bitumen (bitumen 50/70 — 30 t/h and bitumen 70/100 — 2 t/h) are modeled in the GN environment. This study completes the process of modeling the production of petroleum products in an oil refinery using GN.

The OM model contains 8 transitions, 35 places and 8 types of tokens (see Fig. 23).

The meaning of the transitions is as follows:

- VDU — Vacuum distillation plant
- FCCPT — Installation for hydrotreating the feedstock for catalytic cracking
- H-Oil — Hydrocracking of vacuum residues
- FCCU — Fluid Catalytic Cracking Plant
- BU — Installation for the production of bitumen for road surfaces (asphalt)
- 0.5 S — Fuel oil containing a maximum of 0.5 wt. % sulfur
- 1.0 S — Fuel oil containing a maximum of 1.0 wt. % sulfur
- 2.5 S — Fuel oil containing a maximum of 2.5 wt. % sulfur

At the initial moment of GN functioning, token α_0 remains in place l_1 with an initial charactristic:

„Atmospheric Residues (AR), initial amount";

token β_0 remains in place l_9 with an initial characteristic:

„Straight-run vacuum gas oil (SRVGO), initial quantity";

token γ_0 remains in place l_{17} with an initial characteristic:

„Mixture of straight run vacuum residue (SRVR), FCC HCO and FCC SLO, initial quantity";

token δ_0 remains l_{26} with an initial characteristic:

„Vacuum gas oil mixture consisting of SRVGO and H-Oil VGO, initial quantity";

token ε_0 remains in place l_{29} with an initial characteristic:

„Mixture of straight run vacuum residue (SRVR) and hydrocracked vacuum residue, initial quantity";

token ζ_0 remains in place l_{31} with an initial characteristic:

„FO with a maximum sulfur content of 0.5% by weight, initial quantity";

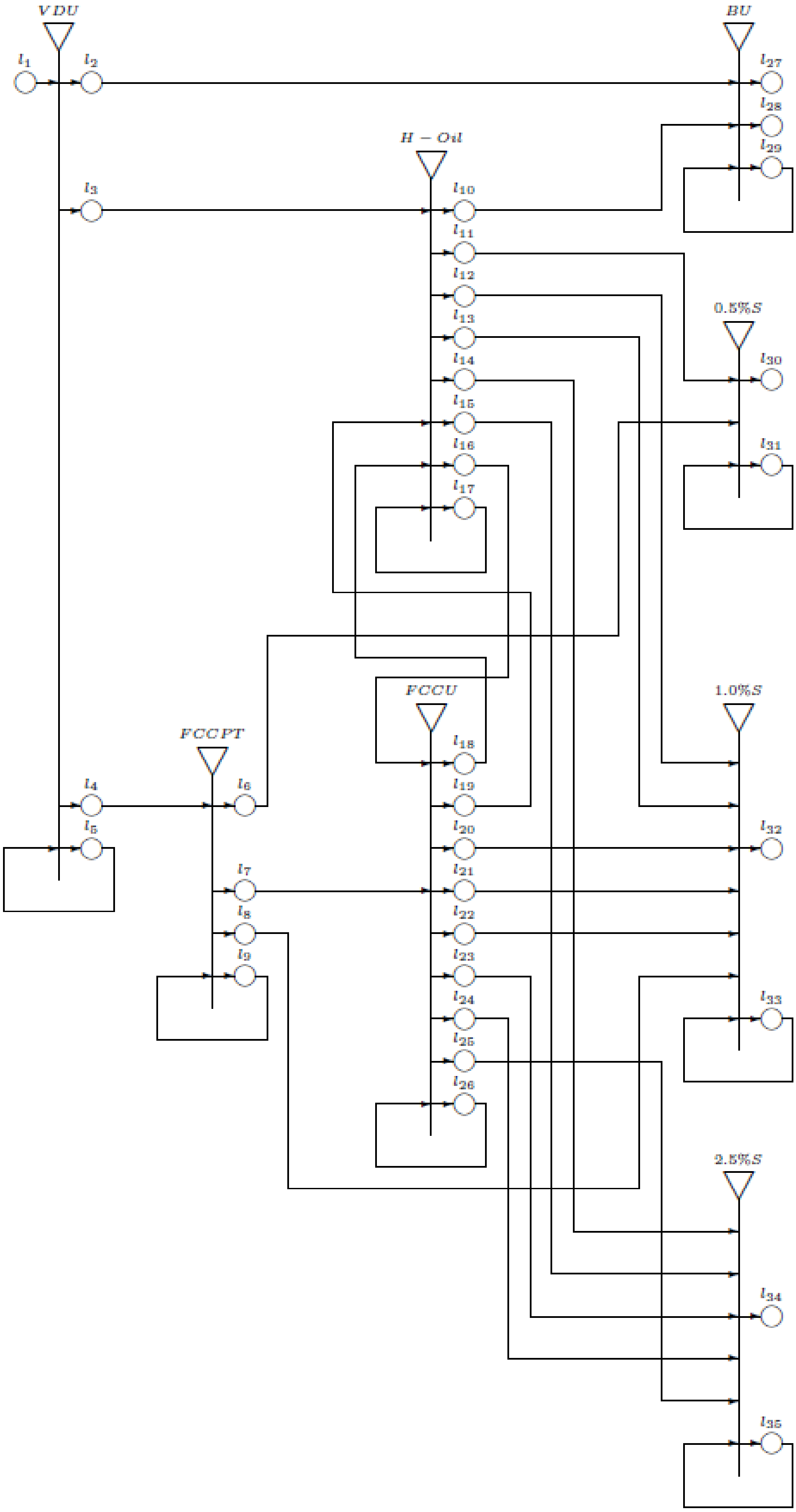

Figure 23. GN model of heavy oil product production in the refinery that is the subject of this study.

token η_0 remains in place l_{33} with an initial characteristic:

„FO with a maximum sulfur content of 1.0 wt%, initial quantity“;

token θ_0 remains in place l_{35} with an initial characteristic:

„FO with a maximum sulfur content of 2.5% by weight, initial quantity“.

In every next moment, tokens α_1, α_2, ... enter into place l_1 with initial characteristics:

„AR, current arriving quantity“.

For brevity, these tokens will be denoted below as α without their (current) subscripts. Similarly, the subscripts of the β, γ and δ tokens will be omitted, the meaning of which will be described below.

The transitions of the generalized net have the following forms.

$$VDU = \left\langle \{l_1, l_5\}, \{l_2, l_3, l_4, l_5\}, \begin{array}{c|cccc} & l_2 & l_3 & l_4 & l_4 \\ \hline l_1 & false & false & false & true \\ l_5 & W_{5,2} & W_{5,3} & W_{5,4} & true \end{array} \right\rangle,$$

where,

$W_{5,2}$ =„there is a request for atmospheric oil residue (AR) from a bitumen plant (BU)",

$W_{5,3}$ =„ there is an AR request from H-Oil“,

$W_{5,4}$ =„ there is an AR request from FCCPT“.

When the α─token enters position l_1 at the next time instant, it enters place l_5 and merges with the α_0 ntoken, which obtains the characteristic:

„ current amount of AR in the tank“.

Regarding the truth values of predicates $W_{5,2}$, $W_{5,3}$, $W_{5,4}$ token α_0 divides into two, three, or four tokensi─the same token α_0 continues to stand in place l_5 with the above-mentioned characteristic, and tokens α^1, α^2 and/or α^3, receive the characteristics accordingly:

„q_1 AR for BU”

in place l_2, where $q_1 \in [0, Q_1]$;

in place l_3, where $q_2 \in [0, Q_2]$;

in place l_4, where $q_3 \in [0, Q_3]$;

Here and henceforth Qi will be the maximum quantity for the i-th component heavy oil product involved in the production of FO and bitumen for road pavement, where $1 \le i \le 26$.

$$FUCPT = \left\langle \{l_4, l_9\}, \{l_6, l_7, l_8, l_9\}, \begin{array}{c|cccc} & l_6 & l_7 & l_8 & l_8 \\ \hline l_1 & false & false & false & true \\ l_9 & W_{9,6} & W_{9,7} & W_{9,8} & true \end{array} \right\rangle,$$

where,

$W_{9,6}$ = „there is a request for HTVGO for the production of FO with maximum sulfur content of 0.5% S“,

$W_{9,7}$ = „there is a request for HTVGO as a feedstock for the catalytic cracking plant (FCCU)“,

$W_{9,8}$ = „there is a request for HTVGO for the production of FO with a maximum sulfur content of 1.0% S“.

Token α^3 from place l_4 enters in place l_9 and merges with the token β_0, which gets the characteristic:

„Current amount of mixture of straight-run vacuum gas oil (SRVGO) and H-Oil vacuum gas oil (H-Oil VGO) in the tank“.

Regarding the truth values of predicates $W_{9,6}$,$W_{9,7}$,$W_{9,8}$, token β_0 divides into two, three and four tokens – the same token β_0 continues to stand in place l_9 with the aforementioned characteristic and the tokens β_1, β_2 and/or β_3 receive the characteristics accordingly:

“q_4 HTVGO for FO with a maximum sulfur content of ≤ 0.5% of FCCPT”

in place l_6, where $q_4 \in [0, Q_4]$;

“q_5 HTVGO for FCCU”

in place l_7, whereo $q_5 \in [0,Q_5]$;

“q_6 HTVGO for FO with a maximum sulfur content of 1.0%”

In place l_8, where $q_6 \in [0,Q_6]$;

$$H - Oil = \langle \{l_3, l_{17}, l_{18}, l_{19}\}, \{l_{10}, l_{11}, l_{12}, l_{13}, l_{14}, l_{15}, l_{16}, l_{17}\},$$

	l_{10}	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{16}
l_1	false	false	false	false	false	false	false	true
l_{17}	$W_{17,10}$	$W_{17,11}$	$W_{17,12}$	$W_{17,13}$	$W_{17,14}$	$W_{17,15}$	$W_{17,16}$	true
l_{18}	false	false	false	false	false	false	false	true
l_{19}	false	false	false	false	false	false	false	true

$\rangle$,

where,

$W_{17,10}$ = „there is a request for H-Oil VTB for bitumen“,

$W_{17,11}$ = „there is a request for H-Oil HAGO for FO 0.5% S“,

$W_{17,12}$ = „there is a request for VGO for FO 1.0% S“,

$W_{17,13}$ = „there is a request for H-Oil VTB for FO 1.0% S“,

$W_{17,14}$ = „there is a request for H-Oil VTB for FO 2.5% S“,

$W_{17,15}$ = „there is a request for VGO for FO 2.5% S“,

$W_{17,16}$ = „there is a request for VGO as feedstock for FCCU“.

Token α^2 from place l_3 enterrs in place l_{17} and merges with γ_0, which gets the characteristic:

„current amount of SRVR in tank“

Regarding the truth values of predicates $W_{17,10}$,…,$W_{17,16}$, token γ_0 divides into two, three, four,…, or seven tokens – the same token γ_0 continues to stand in place l_{17} with the aforementioned characteristic and the tokens γ^1,…, and/or γ^7 receive the characteristics accordingly:

“q_7 H-Oil VTB as a raw material for BU” in place l_{10}, where $q_7 \in [0,Q_7]$;

"q_8 HAGO for FO 0.5% S"

In place l_{11}, where $q_8 \in [0,Q_8]$;

"q_9 VGO for FO 1.0% S"

in place l_{12}, where $q_9 \in [0,Q_9]$;

"q_{10} H-Oil VTB for 1.0% S"

in place l_{13}, where $q_{10} \in [0,Q_{10}]$;

"q_{11} H-Oil VTB for 2.5% S"

in place l_{14}, where $q_{11} \in [0,Q_{11}]$;

"q_{12} VGO for FO 2.5% S"

in place l_{15}, where $q_{12} \in [0,Q_{12}]$;

"q_{13} VGO as a feed for FCCU"

In place l_{16}, where $q_{13} \in [0,Q_{13}]$;

$$FCCU = \langle \{l_7, l_{16}, l_{26}, \}, \{l_{18}, l_{19}, l_{20}, l_{21}, l_{22}, l_{23}, l_{24}, l_{25}, l_{26}\},$$

	l_{18}	l_{19}	l_{20}	l_{21}	l_{22}	l_{23}	l_{24}	l_{25}	l_{26}
l_1	$false$	$false$	$false$	$false$	$false$	$false$	$false$	$false$	$true$
l_{25}	$false$	$false$	$false$	$false$	$false$	$false$	$false$	$false$	$true$
l_{26}	$W_{26,18}$	$W_{26,19}$	$W_{26,20}$	$W_{26,21}$	$W_{26,22}$	$W_{26,23}$	$W_{26,24}$	$W_{26,25}$	$true$

$\rangle$,

where,

$W_{26,18}$ = „there is a request for catalytic cracking slurry oil (SLO) as feed for H-Oil plant",

$W_{26,19}$ = „there is a request for HCO as a feed for H-Oil plant",

$W_{26,20}$ = „there is a request for LCO for FO 1.0% S",

$W_{26,21}$ = „there is a request for HCO for FO 1.0% S",

$W_{26,22}$ = „there is a request for SLO for FO 1.0% S",

$W_{26,23}$ = „there is a request for LCO for FO 2.5% S",

$W_{26,24}$ = „there is a request for HCO for FO 2.5% S",

$W_{26,25}$ = „there is a request for SLO for FO 2.5 % S".

Token α from palce l_9 and token γ from place l_{16} enter into place l_{26} and merges with token δ_0, which gets the characteristic:

„current amount of feedstock for catalytic cracking in a tank".

Regarding the truth values of predicates $W_{26,18},\ldots,W_{26,25}$, token δ_0 divides into two, three,…, or eight tokens – the same token δ_0 continues to stand in place l_{26} with the aforementioned characteristic and the tokens $\delta^1,\ldots$, and/or δ^8 receive the characteristics accordingly:

"q_{14} SLO as raw material for the installation H-Oil"

In place l_{18}, where $q_{14} \in [0,Q_{14}]$;

"q_{15} HCO as raw material for the installation H-Oil"

in place l_{19}, where$q_{15} \in [0,Q_{15}]$;

"q_{16} LCO for FO 1.0% S"

In position l_{20}, where $q_{16} \in [0,Q_{16}]$;

"q_{17} HCO for FO 1.0% S"

in place l_{21}, where $q_{17} \in [0,Q_{17}]$;

"q_{18} SLO for FO 1.0% S"

in place l_{22}, where $q_{18} \in [0,Q_{18}]$;

"q_{19} LCO for 2.5% S"

in place $l_{23}$where $q_{19} \in [0,Q_{19}]$;

"q_{20} HCO for FO 2.5% S"

in place l_{24}, where $q_{20} \in [0,Q_{20}]$;

"q_{21} SLO for FO 2.5% S"

in place l_{25} where $q_{21} \in [0,Q_{21}]$;

$$BU = \left\langle \{l_2, l_{10}, l_{29}\}, \{l_{27}, l_{28}, l_{29}\}, \begin{array}{c|ccc} & l_{27} & l_{28} & l_{29} \\ \hline l_2 & false & false & true \\ l_{10} & false & false & true \\ l_{29} & W_{29,27} & W_{29,28} & true \end{array} \right\rangle,$$

where,

$W_{29,27}$ = „there is a request for road bitumen brand 50/70",

$W_{29,28}$ = „there is a request for road bitumen brand 70/100".

Token α from place and token γ from place l_{10} enter into place l_{29} and merges with token ε_{0}, which gets the characteristic:

„current amount of bitumen feedstock (mixture of SRVR and H-Oil VTB)"

Regarding the truth values of predicates $W_{29,27}$ and $W_{29,28}$, token ε_{0} divides into two or three tokens – the same token ε_0 continues to stand in place l_{29} with the aforementioned characteristic and the tokens ε^1 and ε^2 receive the characteristics accordingly:

"q_{22} Road bitumen, brand 50/70"

in place l_{27} where $q_{22} \in [0,Q_{22}]$;

"q_{23} Road bitumen, brand 70/100"

in place l_{28} where$q_{23} \in [0,Q_{23}]$;

$$0.5\%S = \left\langle \{l_6, l_{11}, l_{31}\}, \{l_{30}, l_{31}\}, \begin{array}{c|cc} & l_{30} & l_{31} \\ \hline l_6 & false & true \\ l_{11} & false & true \\ l_{31} & W_{31,30} & true \end{array} \right\rangle,$$

where,

$W_{31,30}$ = „there is a request for FO with a maximum sulfur content of 0.5 wt.% S".

Token γ from place l_{11} and token β from place l_7 enters into place l_{31} and merges with token ζ_0, which gets the characteristic:

„Requested quantity FO 0.5% S"

When the truth value of the predicates $W_{31,30}$ and $W_{29,28}$ is true, token ζ_0 divides into two tokens – the same token ζ_0,, which continues to stand in place l_{31} with the above mentioned characteristics and token ζ^1 gets the characteristics:

token ε_0 divides into two or three tokens– the same token ε_0 continues to stand in place l_{29} with the aforementioned characteristic and the tokens ε^1 and ε^2 receive the characteristics accordingly:

"q_{24} Requested quantity FO 0.5% S"

in place l_{30} where $q_{24} \in [0,Q_{24}]$;

$$1.0\%S = \left\langle \{l_{12}, l_{13}, l_{20}, l_{21}, l_{22}, l_{33}\}, \{l_{32}, l_{33}\}, \begin{array}{c|cc} & l_{32} & l_{33} \\ \hline l_{12} & false & true \\ l_{13} & false & true \\ l_{20} & false & true \\ l_{21} & false & true \\ l_{22} & false & true \\ l_{33} & W_{33,32} & true \end{array} \right\rangle,$$

where,

$W_{33,32}$ = „there is a request for FO 1.0 % S".

Tokens γ from places l_{12} and l_{13} and tokens δ from places l_{20}, l_{21}, l_{22} enter into place l_{33} and unite with token η_0, which receives the characteristics:

„Current quantity of FO 1.0%S in the tank farm"

When the truth value of the predicate $W_{33,32}$ is true, token η_0 divides into two tokens – the same token η_0, which continues to stand in place l_{33} with the above mentioned characteristics and token η^1 gets the characteristics:

"q_{25} Claimed quantity FO 1.0 %S"

in place l_{32} where $q_{25} \in [0,Q_{25}]$;

$$2.5\%S = \left\langle \{l_8, l_{14}, l_{15}, l_{23}, l_{24}, l_{25}, l_{35}\}, \{l_{34}, l_{35}\}, \begin{array}{c|cc} & l_{34} & l_{35} \\ \hline l_8 & false & true \\ l_{14} & false & true \\ l_{15} & false & true \\ l_{23} & false & true \\ l_{24} & false & true \\ l_{25} & false & true \\ l_{35} & W_{35,34} & true \end{array} \right\rangle,$$

where,

$W_{35,34}$ = „there is a request for a certain quantity of FO 2.5% S".

Tokens γ from places l_{14} and l_{15} and δ- tokens from places l_{23}, l_{24}, l_{25} enter into place l_{35} and unite with token θ_0, which receives the characteristics:

„current amount of FO 2.5% S in the tank farm“

When the truth value of the predicate $W_{35,34}$ is true, token θ_0 divides into two tokens – the same token θ_0, which continues to stand in place l_{35} with the above-mentioned characteristic and token θ^1 gets the characteristics:

“q_{26} Requested quantity FO 2.5 % S ”

in place l_{42} where $q_{26} \in [0, Q_{26}]$;

Similar to the modeling of the production processes of various grades of automotive gasoline, automotive diesel and fuel gas, propane-butane, propylene and polypropylene, the production processes of various grades of heavy petroleum products in an oil refinery were also possible to be modeled using generalized nets. All these processes are complex and parallel, and their modeling using GN allows to avoid the shortcomings of linear and even dynamic programming (where the difficulty comes from the inability to reflect the logic of cause-and-effect relationships). The combination of the four already established separate GN models, which simulate in detail the production processes of all petroleum products, in another higher GN hierarchy is the next step in modeling the production of petroleum products in an oil refinery using GN. Through this series of published studies [160, 198, 199 and 220] a new approach to modeling processes in an oil refinery is proposed, which is more global than those currently available.

Publications for Chapter 5

The presented results are included in the article:

223. Stratiev, D.; Dimitriev, A.; Stratiev, D.; Atanassov, K. Generalized Net Model of Heavy Oil Products’ Manufacturing in Petroleum Refinery. Mathematics 2023, 11, 4753.

CHAPTER 6

GENERALIZED NET MODEL OF PROCESSES IN AN OIL REFINERY

This chapter represents the final part of the overall study of modeling the processes of petroleum product production in a refinery.

The GN contains 23 transitions and 90 places (see Fig. 25). The meanings of some of the transitions are related to individual plants, as follows:

Z_1 Organizational activity in the oil refinery

Z_2 Absorption gas fractionation unit (AGFU)

Z_3 Catalytic reforming (CatRef)

Z_4 VDU-2

Z_7 LPG tanks

Z_9 LPG hydrotreating (LPG HDS)

Z_{10} FCC-PT

Z_{11} H-Oil

Z_{12} CGFU

Z_{13} Bitumen

Z_{14} HDS1-3,5

Z_{15} FCC

Z_{16} Iso-C_4

Z_{17} MTBE

Z_{18} Claus unit-4

Z_{19} Fuel gas (FG) Storage

Z_{20} Alkylation

Z_{21} Prime G

Z_{22} Polypropylene Unit

Z_{23} Production of final products by mixing the various components and their shipment.

The remaining transitions play an auxiliary role related to the GN notation and this will be discussed in the text below.

l_1 quantity and quality of crude oil

l_2 purchase order for final petroleum product, quantity, customer

l_3 information about final petroleum products on the world market, quantity, producer

l_4 dry gas for AGFU, quantity

l_5 LPG,quantity

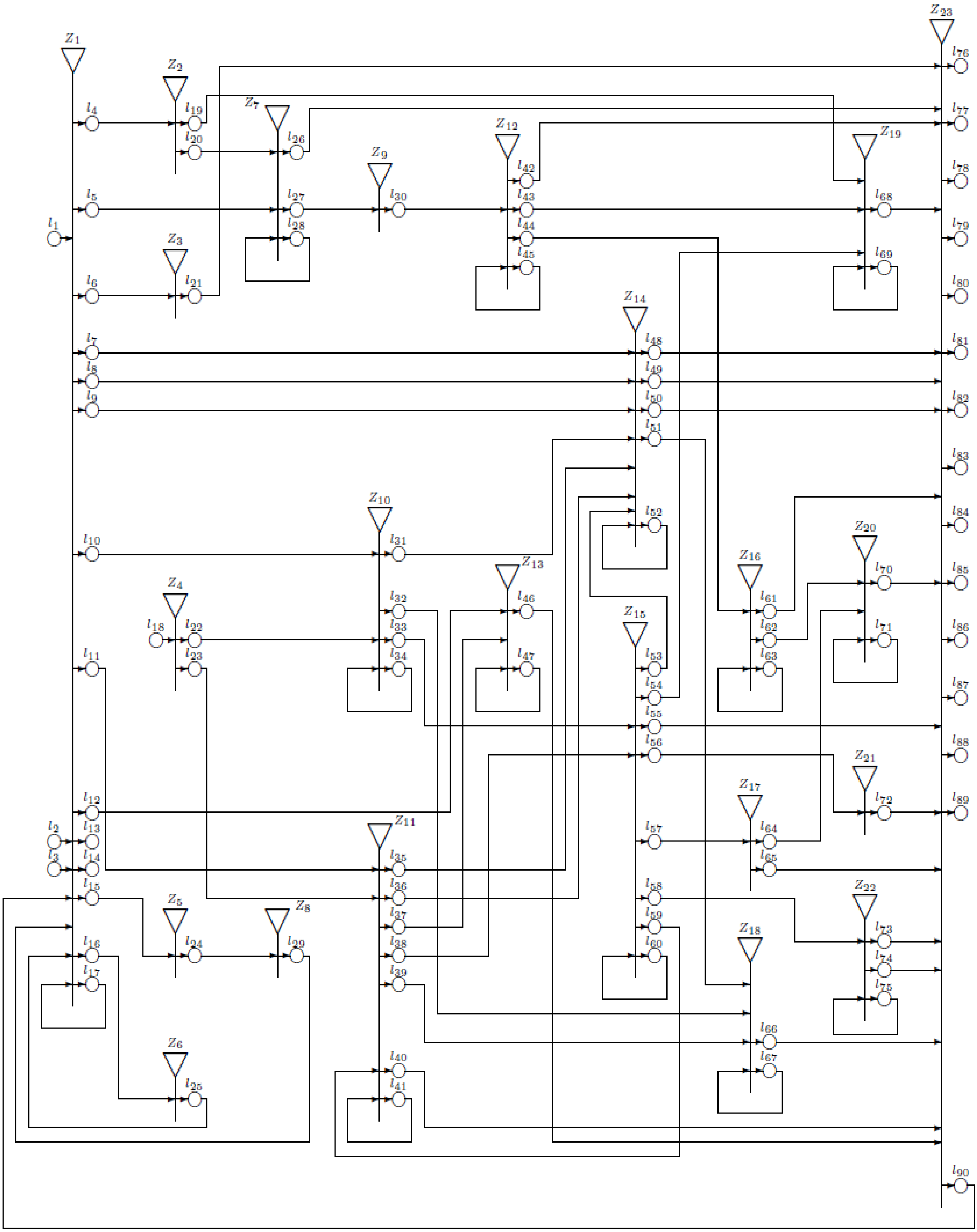

Figure 25. GN model of oil refinery processes.

l_6 quantity of heavy low-octane gasoline, feedstock for catalytic reforming

l_7 light low octane gasoline, quantity

l_8 kerosene, quantity

l_9 diesel, quantity

l_{10} vacuum gas oil, quantity

l_{11} straight run vacuum residue, quantity, feedstock for hydrocracking H-Oil

l_{12} straight run vacuum residue, quantity, feedstock for road bitumen

l_{13} (positive or negative) response from a current order

l_{14} information about what products of specific quality are offered for sale on the world market

l_{15} information on the types of low octane gasoline available at the plant and a list of the types of low octane gasoline that dealers purchase

l_{16} decision to purchase the most appropriate type of crude oil financial assessment

l_{17} archive of the complete process and the decision maker

l_{18} atmospheric residue, quantity

l_{19} fuel gas – final product, quantity

l_{20} fuel gas for CGFU, quantity

l_{21} reformate for mixing, quantity

l_{22} vacuum gas oil, quantity

l_{23} vacuum residue, quantity

l_{24} ICrA results on existing and potential crude oil data

l_{25} financial activities for the purchase of certain types of crude oil

l_{26} Propane-butane (LPG) for sale, quantity

l_{27} Propane-butane for hydrotreating (LPG HDS), quantity

l_{28} current status of the LPG tank farm (including the quantity in it)

l_{29} result of ICrA and other correlation analyses and selection of the most suitable oil

l_{30} LPG for CGFU, quantity

l_{31} diesel for HDS1-3.5, quantity

l_{32} H_2S for Claus unit, quantity

l_{33} HTVGO for FCC, quantity

l_{34} current status of FCC-PT

l_{35} low octane gasoline for HDS1-3.5, quantity

l_{36} diesel for HDS1-3.5, quantity

l_{37} H-Oil VTB for bitumen, quantity

l_{38} H-Oil VGO for catalytic cracking (FCC), quantity

l_{39} H_2S for the Claus unit, quantity

l_{40} Partially blended fuel oil (PBFO) for sale, quantity

l_{41} current status of H-Oil

l_{42} LPG for sale, quantity

l_{43} Fuel gas for storage, quantity

l_{44} Normal butane for C4 isomerization, quantity

l_{45} current status of CGFU

l_{46} Bitumen for sale, quantity

l_{47} current status of bitumen unit

l_{48} Low octane hydrotreated gasoline (HTN) for sale, quantity

l_{49} Hydrotreated kerosene for sale, quantityl_{50} Hydrotreated diesel for sale, quantity

l_{51} H2S for Claus installation, quantity

l_{52} current status of HDS1-3.5

l_{53} LCO for HDS1-3.5, quantity

l_{54} Dry gas for storage, quantity

l_{55} HCO for sale, quantity

l_{56} Cracked gasoline (CN) for blending, quantity

l_{57} C4 for MTBE, quantity

l_{58} Propylene for polypropylene production, quantity

l_{59} FCC SLO for H-Oil, Quantity

l_{60} current status of the FCC unit

l_{61} Isobutane for blending in gasoline production, quantity

l_{62} Isobutane as a feedstock for sulfuric acid alkylation, quantity

l_{63} current status of normal butane isomerization

l_{64} C_4 olefins for sulfuric acid alkylation (Alkylation), quantity

l_{65} MTBE for sale, quantity

l_{66} Sulfur for sale, quantity

l_{67} current status of the Claus unit

l_{68} Fuel gas for combustion in the refinery's process furnaces, quantity

l_{69} current status of the fuel gas storage tank farm (FG Storage)

l_{70} Alkylate for mixing, quantity

l_{71} current status of sulfuric acid alkylation

l_{72} Hydrotreated cracked gasoline for blending, quantity

l_{73} Propylene for sale, quantity

l_{74} Polypropylene for sale, quantity

l_{75} current status of the polypropylene production plant

l_{76} Fuel gas, quantity

l_{77} Propane-butane, quantity

l_{78} Low octane gasoline, quantity

l_{79} Sulfur, quantity

l_{80} Jet A-1, quantity

l_{81} Euro diesel, quantity

l_{82} Automotive gasoline A-95 (mineral / bio), quantity

l_{83} Automotive gasoline A-98, quantity

l_{84} Automotive gasoline A-100 (bio), quantity

l_{85} Propylene, quantity

l_{86} Polypropylene, quantity

l_{87} Fuel oil, quantity

l_{88} Marine fuel with 0.5% sulfur, quantity

l_{89} Bitumens, quantity

l_{90} archive information

All the tokens related to crude oil will be denoted as π-tokens, for brevity those without indices; tokens related to external or output information as ι-tokens; tokens related to decision-making processes as δ-tokens; and the α-token, which remains permanently at position l_{17}, represents the archive of the complete process and the decision-maker. Of course, in a more detailed process this token can be replaced by a whole subnet in which the archive will have its own transition, places and tokens, and the activities of the decision-maker can be described in substantially more detail. At some point after the arrival of some ι-token, the α-token splits into two tokens – the same α-token and a δ-token.

In some steps of the GN functioning, the ι-token enters the l_2 position with the initial characteristic:

“purchase order for final petroleum product, quantity, customer”,

or is placed in place l_3 with the initial characteristic:

“information about final petroleum products on the world market, quantity, producer ”.

The structure of the model corresponds to the real processes occurring in an oil refinery. The LUKOIL Neftohim Burgas refinery is given as an example. Therefore, no restrictions are imposed in the model.

$$Z_1 = \langle \{l_1, l_2, l_3, l_{17}, l_{25}, l_{41}, l_{84}\}, \{l_4, l_5, l_6, l_7, l_8, l_9, l_{10}, l_{11}, l_{12}, l_{13}, l_{14}, l_{15}, l_{16}, l_{17}\},$$

	l_4	l_5	l_6	l_7	l_8	l_9	l_{10}	l_{11}	l_{12}	l_{13}	l_{14}	l_{15}	l_{16}	l_{17}
l_1	$W_{1,4}$	$W_{1,5}$	$W_{1,6}$	$W_{1,7}$	$W_{1,8}$	$W_{1,9}$	$W_{1,10}$	$W_{1,11}$	$W_{1,12}$	F	F	F	F	F
l_2	F	F	F	F	F	F	F	F	F	F	F	F	F	T
l_3	F	F	F	F	F	F	F	F	F	F	F	F	F	T
l_{17}	F	F	F	F	F	F	F	F	F	$W_{17,13}$	$W_{17,14}$	$W_{17,15}$	$W_{17,16}$	T
l_{25}	F	F	F	F	F	F	F	F	F	F	F	F	F	T
l_{41}	F	F	F	F	F	F	F	F	F	F	F	F	F	T
l_{90}	F	F	F	F	F	F	F	F	F	F	F	F	F	T

$\rangle$,

where,

$W_{1,4}$ = „ there is a need for dry gas for AFGU“,

$W_{1,5}$ = „ there is a need for LPG for storage LPG“,

$W_{1,6}$ = „ there is a need for heavy low octane gasoline (HN) for CatRef “,

$W_{1,7}$ = „ there is a need for light low octane gasoline (LN) for HDS1-3.5“,

$W_{1,8}$ = „ there is a need for kerosene for HDS1-3,5“,

$W_{1,9}$ = „ there is a need for diesel for HDS1-3.5“,

$W_{1,10}$ = „ there is a need for vacuum gas oil (VGO) for FCC-PT “,

$W_{1,11}$ = „ there is a need for vacuum residue (VR) for bitumen “,

$W_{1,12}$ = „ there is a need for VR for H-Oil “,

$W_{17,13}$ = „ there is a decision for the current order “,

$W_{17,14}$ = „there is an opportunity to announce what kind of products of a specific quality are available for sale”,

$W_{17,15}$ = „ there is data on new types of crude oil that dealers can buy “,

$W_{17,16}$ = „ the most suitable crude oil for purchase is determined “.

Regarding the truth values of predicates $W_{1,4}$, $W_{1,5}$, $W_{1,6}$, $W_{1,7}$, $W_{1,8}$, $W_{1,9}$, $W_{1,10}$, $W_{1,11}$, $W_{1,12}$, token π from place l_1 divides into one, two, three, …, or eight π-tokens, which enter into place l_4, l_5, . . . , l_{12} with characteristics:

„ dry gas for AGFU, quantity “,

„LPG, quantity“,

„ heavy low octane gasoline for catalytic reforming (CatRef) quantity “,

„ light low octane gasoline quantity “,

" kerosene, quantity ",

„ Diesel, quantity “,

„ Vacuum gas oil (VGO), quantity “,

„ Vacuum residue (VR), quantity “,

„ Vacuum residue (VR), quantity “.

Regarding the truth values of predicates $W_{17,13}$,$W_{17,14}$,$W_{17,15}$, $W_{17,16}$, token α from place l_{17} divides into two tokens: the same token α, which continues to stand in place $l_{17}$and token δ, that eners in place l_{13} with the characteristic:

“(positive or negative) response from the current order",

or in place l_{14} with the characteristic:

“providing information on what kind of products of specific quality are available for sale on the world market “,

or in place l_{15} with the characteristic:

“information about the existing types of crude oil at the plant and a list of types of crude oil that traders can purchase “,

or in place l_{16} with the characteristic:

“decision to purchase the most suitable type of crude oil, financial assessment ”.

When one of the tokens δ from place l_{25}, l_{29} or l_{90} enters into place l_{17}, it merges with the token α and the last token gets the characteristic:

“up-to-date information on the status of the processes taking place in the petrochemical plant”.

$$Z_2 = \langle \{l_4\}, \{l_{19}, l_{20}\}, \begin{array}{c|cc} & l_{19} & l_{20} \\ \hline l_4 & W_{4,19} & W_{4,20} \end{array} \rangle,$$

where,

$W_{4,19}$ = „ there is a need for fuel gas as a final product“,

$W_{4,20}$ = „ there is a need for fuel gas for CGFU “.

Regarding the truth values of predicates $W_{4,19}$ and $W_{4,20}$, π-token from place l_4 enters the corresponding starting place or divides into two tokens that enter the place l_{19} with the characteristic:

“fuel gas for final product, quantity “

or in place l_{20} with the characteistic:

“fuel gas for CGFU, quantity ”.

$$Z_3 = \langle \{l_4\}, \{l_{21}\}, \begin{array}{c|c} & l_{21} \\ \hline l_4 & T \end{array} \rangle.$$

The token from place l_6 enters in place l_{21} with the characteistic:

“reformate for final product, quantity “.

π-tokens with the initial characteristic:

“Atmospheric residues, quantity “

enter the net through place l_{18}.

$$Z_4 = \langle \{l_{18}\}, \{l_{22}, l_{23}\}, \begin{array}{c|cc} & l_{22} & l_{23} \\ \hline l_6 & W_{6,22} & W_{6,23} \end{array} \rangle,$$

where,

$W_{6,22}$ = „ there is a need for VGO for FCC-PT “,

$W_{6,23}$ = „ there is a need for VGO for H-Oil “.

Regarding the truth values of predicates $W_{6,22}$ and $W_{6,23}$, token from place l_6 enters the corresponding starting position or divides into two tokens that enter place l_{22} with the characteristic:

„VGO, quntity“

Or in place l_{23} with the characteristic:

„VR, quantity“.

$$Z_5 = \langle \{l_{15}\}, \{l_{24}\}, \begin{array}{c|c} & l_{24} \\ \hline l_{15} & T \end{array} \rangle.$$

Token δ from place l_{15} enters into place l_{24} with the feature "results of inter-criteria analysis (ICrA, see [859]) on existing and potential crude oil data “.

$$Z_6 = \langle \{l_{16}\}, \{l_{25}\}, \begin{array}{c|c} & l_{25} \\ \hline l_{16} & T \end{array} \rangle.$$

Token δ from place l_{16} enters into place l_{25} with the characteristic:

„ financial activities for the purchase of specified crude oils”.

$$Z_7 = \langle \{l_5, l_{20}, l_{28}\}, \{l_{26}, l_{27}, l_{28}\}, \begin{array}{c|ccc} & l_{26} & l_{27} & l_{28} \\ \hline l_5 & F & F & T \\ l_{20} & F & F & T \\ l_{28} & W_{28,26} & W_{28,27} & T \end{array} \rangle,$$

where,

$W_{28,26}$ = „ there is a need for LPG for sale “,

$W_{28,27}$ = „ there is a need for LPG for LPG HDS “.

Regarding the truth values of predicates $W_{28,26}$ and $W_{28,27}$, the token from place l_{28} divides into two or three tokens that enter into place l_{26} or in plce l_{27} and (required) in placel_{28}, where they receive, respectively, the characteristic:

„ LPG for sale, quantity “,

or

„ LPG for LPG HDS, quantity “,

or

„ current status of the LPG tank farm(including the quantity in it)“,

$$Z_8 = \langle \{l_{24}\}, \{l_{29}\}, \begin{array}{c|c} & l_{29} \\ \hline l_{24} & T \end{array} \rangle.$$

The token δ from place l_{24} enters in place l_{29} with the characteristic:

„ result of ICrA and other correlation analyses and selection of the most suitable crude oil “.

$$Z_9 = \langle \{l_{27}\}, \{l_{30}\}, \begin{array}{c|c} & l_{30} \\ \hline l_{27} & T \end{array} \rangle.$$

The token from place l_{27} enters in place l_{30} with the characteristic:

„ LPG for CGFU, quantity “.

$$Z_{10} = \langle \{l_{10}, l_{22}, l_{34}\}, \{l_{31}, l_{32}, l_{33}, l_{34}\}, \begin{array}{c|cccc} & l_{31} & l_{32} & l_{33} & l_{34} \\ \hline l_{10} & F & F & F & T \\ l_{22} & F & F & F & T \\ l_{34} & W_{34,31} & W_{34,32} & W_{34,33} & T \end{array} \rangle,$$

where,

$W_{34,31}$ = „there is a need for FCC-PT diesel for HDS1-3.5“,

$W_{34,32}$ = „there is a need for hydrogen sulfide (H_2S) for a Claus unit“,

$W_{28,34}$ = „there is a need for hydrotreated vacuum gas oil (HTVGO) for FCC “.

With respect to the truth values of the predicates $W_{34,31}$,$W_{34,32}$ and $W_{34,33}$, the token at place l_{34} is divided into two, three or four tokens, which enter place l_{31} and/or l_{32} and/or place l_{33} and place l_{34}, where they receive, respectively, the characteristic:

„ Diesel for HDS1-3.5, quantity“,

„H_2S for the Claus unit, quantity “,

„HTVGOfor FCC, quantity“,

„ current status of FCC-PT“.

$$Z_{11} = \langle \{l_{11}, l_{23}, l_{41}, l_{59}\}, \{l_{35}, l_{36}, l_{37}, l_{38}, l_{39}, l_{40}, l_{41}\}, \begin{array}{c|ccccccc} & l_{35} & l_{36} & l_{37} & l_{38} & l_{39} & l_{40} & l_{41} \\ \hline l_{11} & F & F & F & F & F & F & T \\ l_{23} & F & F & F & F & F & F & T \\ l_{41} & W_{41,35} & W_{41,36} & W_{41,37} & W_{41,38} & W_{41,39} & W_{41,40} & T \\ l_{59} & F & F & F & F & F & F & T \end{array} \rangle,$$

where,

$W_{41,35}$ = „ there is a need for low octane gasoline for HDS1-3.5“,

$W_{41,36}$ = „ there is a need for diesel for HDS1-3.5“,

$W_{41,37}$ = „ there is a need for hydrocracked vacuum residue (VTB) for bitumen“,

$W_{41,38}$ = „ there is a need for hydrocracked VGO (HCKVGO) for FCC“,

$W_{41,39}$ = „ there is a need for H_2S for the Claus unit“,

$W_{41,40}$ = „ there is a need for partially blended fuel oil (PBFO) for sale “.

With respect to the truth values of the predicates $W_{41,35}, W_{41,36}, \ldots, W_{41,40}$, the token at place l_{41} is divided into two, three or . . . , or seven tokens, which enter place l_{35} and/or place l_{36} and/or . . . , and/or place l_{40}, and (mandatory) in place l_{41}, where they receive, respectively, the characteristic:

„ low octane gasoline for HDS1-3.5, quantity “,

„ diesel for HDS1-3.5, quantity “,

„ H-Oil VTB for bitumen, quantity “,

"H-Oil VGO for FCC, quantity",

"H_2S for Claus unit, quantity",

or

"PBFO for sale, quantity",

and

"current status of H-Oil".

$$Z_{12} = \langle \{l_{30}, l_{45}\}, \{l_{42}, l_{43}, l_{44}, l_{45}\}, \begin{array}{c|cccc} & l_{42} & l_{43} & l_{44} & l_{45} \\ \hline l_{30} & F & F & F & T \\ l_{45} & W_{45,42} & W_{45,43} & l_{45,44} & T \end{array} \rangle,$$

where,

$W_{45,42}$ = „ there is a need for LPG for sale“,

$W_{45,43}$ = „ there is a need for fuel gas for FG storage“,

$W_{45,44}$ = „ there is a need for n-butane for C4 isomerization“,

Regarding the truth values of the predicates $W_{45,42}, W_{45,43}$ and $W_{45,44}$, the token from place l_{45} is divided into two, three or four tokens, which enter place l_{42} and/or place l_{43} and/or place l_{44}, and (mandatory) in place l_{45}, where they receive, respectively, the characteristic:

"LPG for sale, quantity",

"Fuel gas for storage in the tank farm, quantity",

or

"Normal butane for C4 isomerization, quantity",

and

"current state of CGFU",

$$Z_{13} = \langle \{l_{12}, l_{37}, l_{47}\}, \{l_{46}, l_{47}\}, \begin{array}{c|cc} & l_{46} & l_{47} \\ \hline l_{12} & F & T \\ l_{37} & F & T \\ l_{47} & W_{47,46} & T \end{array} \rangle,$$

where,

$W_{47,46}$ = „ there is a need for bitumen for sale “.

When the truth value a of the predicate $W_{47,46}$ is true, the token at place l_{47} is divided into two tokens, which enter place l_{46} and (mandatory) at place l_{47}, where they receive the characteristics:

“Bitumen for sale, quantity”

and

“current status of bitumen unit”,

$Z_{14} = \langle\{l_7, l_8, l_9, l_{31}, l_{35}, l_{36}, l_{52}\}, \{l_{48}, l_{49}, l_{50}, l_{51}, l_{52}\},$

	l_{48}	l_{49}	l_{50}	l_{51}	l_{52}
l_7	F	F	F	F	T
l_8	F	F	F	F	T
l_9	F	F	F	F	T
l_{31}	F	F	F	F	T
l_{35}	F	F	F	F	T
l_{36}	F	F	F	F	T
l_{52}	$W_{52,48}$	$W_{52,49}$	$W_{52,50}$	$W_{52,51}$	T

$\rangle,$

where,

$W_{52,48}$ = “there is a need for hydrotreated low octane gasoline (HTN) for sale”,

$W_{52,49}$ = “there is a need for hydrotreated kerosene (HTK) for sale”,

$W_{52,50}$ = “there is a need for hydrotreated diesel (HTD) for sale”,

$W_{52,51}$ = “there is a need for H2S for the Claus plant”.

With respect to the truth values of the predicates $W_{52,48}$, . . . ,$W_{52,51}$, the token at place l_{52} is divided into two, three or . . . , of five tokens that enter place l_{48} and/or place l_{49} and/or . . . , and/or place l_{51}, and (mandatory) in place l_{52}, where they receive the characteristic:

"HTN (hydrotreated low octane gasoline) for sale, quantity",

"HTK (hydrotreated kerosene) for sale, quantity",

"HTD (hydrotreated diesel) for sale, quantity",

"H2S for Claus plant, quantity",

and

"current status of HDS1-3.5", respectively.

$Z_{15} = \langle\{l_{33}, l_{38}, l_{60}\}, \{l_{53}, l_{54}, l_{55}, l_{56}, l_{57}, l_{58}, l_{59}, l_{60}\},$

	l_{53}	l_{54}	l_{55}	l_{56}	l_{57}	l_{58}	l_{59}	l_{60}
l_{33}	F	F	F	F	F	F	F	T
l_{38}	F	F	F	F	F	F	F	T
l_{60}	$W_{60,53}$	$W_{60,54}$	$W_{60,55}$	$W_{60,56}$	$W_{60,57}$	$W_{60,58}$	$W_{60,59}$	T
l_{59}	F	F	F	F	F	F	F	T

$\rangle,$

where,

$W_{60,53}$ = “there is a need for LCO for HDS1-3.5”,

$W_{60,54}$ = “there is a need for dry gas for storage in the FG tank farm”,

$W_{60,55}$ = “there is a need for HCO for blending in KG and sale”,

$W_{60,56}$ = “there is a need for cracked gasoline (CN) for the Prime G plant”,

$W_{60,57}$ = “there is a need for C_4 (butane-butylene fraction) for MTBE”,

$W_{60,58}$ = “there is a need for C_3 fraction from catalytic cracking for polypropylene”,

$W_{60,59}$ = “there is a need for catalytic cracking slurry oil (FCCSLO) as a raw material component for H-Oil”.

Regarding the truth values of the predicates $W_{60,53}$, . . . ,$W_{60,59}$, the token from place l_{60} is divided into two, three or . . . , or eight tokens that enter position l_{53} and/or place l_{54} and/or . . . , and/or place l_{59}, and (mandatory) m place l_{60}, where they receive the characteristic:

"LCO for HDS1-3.5, quantity",

"Dry gas for storage in tank farm, quantity",

"HCO for sale, quantity",

"Cracked gasoline for blending, quantity",

"C_4 for MTBE, quantity",

"C_3 for polypropylene, quantity",

or

"FCC SLO for H-Oil, quantity",

and

"Current FCC status", respectively.

$$Z_{16} = \langle \{l_{44}, l_{63}\}, \{l_{61}, l_{62}, l_{63}\}, \begin{array}{c|ccc} & l_{61} & l_{62} & l_{63} \\ \hline l_{44} & F & F & T \\ l_{63} & W_{63,61} & W_{63,62} & T \end{array} \rangle,$$

where,

$W_{63,61}$ = “isobutane is needed for mixing”,

$W_{63,62}$ = “isobutane is needed for alkylation”.

Regarding the truth values of the predicates $W_{63,61}$ and $W_{63,62}$, the core at place l_{63} is divided into two or three tokens, which enter position l_{61} or place l_{62} and (mandatory) at place l_{63}, where they are combined to obtain the characteristic:

“Isobutane for mixing, quantity”,

or

“Isobutane for alkylation, quantity”,

and

“current state of isomerization”, respectively.

$$Z_{17} = \langle \{l_{57}\}, \{l_{64}, l_{65}\}, \begin{array}{c|cc} & l_{64} & l_{65} \\ \hline l_{57} & W_{57,64} & W_{57,65} \end{array} \rangle,$$

where,

$W_{57,64}$ =“there is a need for C_4 olefins for alkylation”,

$W_{57,65}$ =“there is a need for MTBE for sale”,

Regarding the truth values of the predicates $W_{57,64}$ and $W_{57,65}$, the token from place l_{57} enters place l_{64} with the characteristic:

“C_4 olefins for alkylation, quantity”

or place $l65$ with the characteristic:

“MTBE for sale, quantity”.

$$Z_{18} = \langle \{l_{32}, l_{39}, l_{51}, l_{67}\}, \{l_{66}, l_{67}\}, \begin{array}{c|cc} & l_{66} & l_{67} \\ \hline l_{32} & F & T \\ l_{39} & F & T \\ l_{51} & F & T \\ l_{67} & W_{67,66} & T \end{array} \rangle,$$

where,

$W_{67,66}$ = "needs sulfur for sale".

When the predicate $W_{67,66}$ is true, the token at place l_{67} is split into two tokens, which enter place l_{66} and (mandatory) place l_{67}, where they receive the characteristics:

"Sulfur for sale, quantity"

and

"current status of the Claus plant", respectively.

$$Z_{19} = \langle \{l_{19}, l_{43}, l_{54}, l_{69}\}, \{l_{68}, l_{69}\}, \begin{array}{c|cc} & l_{68} & l_{69} \\ \hline l_{19} & F & T \\ l_{43} & F & T \\ l_{54} & F & T \\ l_{69} & W_{69,68} & T \end{array} \rangle,$$

where,

$W_{69,68}$ = “there is a need for fuel gas for combustion in the process furnaces”.

When the truth value of the predicate $W_{69,68}$ is true, the token at place l_{69} is divided into two tokens, which enter place l_{68} and (mandatory) at place l_{69}, where they receive the characteristics:

“Fuel gas for combustion in the process furnaces, quantity”

and

“current state of the fuel gas storage tank park (FG Storage)”, respectively.

$$Z_{20} = \langle \{l_{62}, l_{64}, l_{71}\}, \{l_{70}, l_{71}\}, \begin{array}{c|cc} & l_{70} & l_{71} \\ \hline l_{19} & F & T \\ l_{43} & F & T \\ l_{54} & F & T \\ l_{71} & W_{71,70} & T \end{array} \rangle,$$

where,

$W_{71,70}$ = "there is a need for alkylate for mixing".

When the predicate $W_{71,70}$ is True, the token at position l_{71} is split into two tokens, which enter place l_{70} and (mandatory) placen l_{71}, where they receive the characteristics:

"Alkylate for mixing, amount"

and

"current alkylation status", respectively.

$$Z_{21} = \langle \{l_{56}\}, \{l_{72}\}, \begin{array}{c|c} & l_{72} \\ \hline l_{56} & T \end{array} \rangle.$$

The token from place l_{56} enters position l_{72} with the characteristic:

"Hydrotreated cracked gasoline for blending, quantity".

$$Z_{22} = \langle \{l_{58}, l_{75}\}, \{l_{73}, l_{74}, l_{75}\}, \begin{array}{c|ccc} & l_{73} & l_{74} & l_{75} \\ \hline l_{58} & F & F & T \\ l_{75} & W_{75,73} & W_{75,74} & T \end{array} \rangle,$$

where,

$W_{75,73}$ = "there is a need for propylene for sale",

W75,74 = "there is a need for polypropylene for sale".

Regarding the truth values of the predicates $W_{75,73}$ and W75,74, the token at place l_{75} is divided into two or three tokens, which enter place l_{73} or place l_{74} and (mandatory) at place l_{75}, where they are combined, obtaining the characteristics:

"Propylene for sale, quantity", or

"Polypropylene for sale, quantity",

and

"current state of the propylene and polypropylene complex", respectively.

$$Z_{23} = \langle \{l_{21}, l_{26}, l_{40}, l_{42}, l_{46}, l_{48}, l_{49}, l_{50}, l_{55}, l_{61}, l_{65}, l_{67}, l_{69}, l_{71}, l_{72}, l_{73}\},$$

$$\{l_{75}, l_{76}, l_{77}, l_{78}, l_{79}, l_{80}, l_{81}, l_{82}, l_{83}, l_{84}, l_{85}, l_{86}, l_{87}, l_{88}, l_{89}\},$$

	l_{76}	l_{77}	l_{78}	l_{79}	l_{80}	l_{81}	l_{82}	l_{83}	l_{84}	l_{85}	l_{86}	l_{87}	l_{88}	l_{89}	l_{90}
l_{21}	F	F	F	F	F	F	T	T	T	F	F	F	F	F	T
l_{26}	F	T	F	F	F	F	F	F	F	F	F	F	F	F	T
l_{40}	F	F	F	F	F	F	F	F	F	F	F	F	T	T	T
l_{42}	F	T	F	F	F	F	F	F	F	F	F	F	F	F	T
l_{46}	F	F	F	F	F	F	F	F	F	F	F	F	F	T	T
l_{48}	F	F	T	F	F	F	T	F	F	F	F	F	F	F	T
l_{49}	F	F	F	F	T	T	F	F	F	F	F	F	F	F	T
l_{50}	F	F	F	F	F	T	F	F	F	F	F	F	F	F	T
l_{55}	F	F	F	F	F	F	F	F	F	F	F	T	T	F	T
l_{61}	F	F	F	F	F	F	T	T	T	F	F	F	F	F	T
l_{65}	F	F	F	F	F	F	T	T	T	F	F	F	F	F	T
l_{66}	F	F	F	T	F	F	F	F	F	F	F	F	F	F	T
l_{68}	T	F	F	F	F	F	F	F	F	F	F	F	F	F	T
l_{70}	F	F	F	F	F	F	T	T	T	F	F	F	F	F	T
l_{72}	F	F	F	F	F	F	T	T	T	F	F	F	F	F	T
l_{73}	F	F	F	F	F	F	F	F	F	T	F	F	F	F	T
l_{74}	F	F	F	F	F	F	F	F	F	F	T	F	F	F	T

$\rangle$.

Each π-token is divided into two tokens: one π-token, which enters the place defined by the corresponding predicate in the indexed matrix (IM) with the characteristic as follows:

in position l_{76}: "Fuel gas, quantity",

in position l_{77}: "LPG, quantity",

in position l_{78}: "Low octane gasoline, quantity",

in position l_{79}: "Sulfur, quantity",

in position l_{80}: "JetA-1, quantity",

in position l_{81}: "Euro-Diesel, quantity",

in position l_{82}: "A-95 (mineral/bio), quantity",

in position l_{83}: "A-98H, quantity",

in position l_{84}: "A-100H (bio), quantity",

in position l_{85}: "Propylene, quantity",

in position l_{86}: "Polypropylene, quantity",

in position l_{87}: "Fuel oil, quantity",

in position l_{88}: "RMF 0.5% sulfur (naval fuel), quantity”,

in position l_{89}: “Bitumen, quantity”,

and a δ-token, which enters place l_{90} with the same characteristic (archive information).

This chapter of the dissertation theoretically explores the application of GN to modeling the actual processes that occur in oil refining and the production of final commodity petroleum products.

It can be seen that the current GN model includes as subnets the previous models as follows:places l_{21}, l_{48}, l_{61}, l_{65}, l_{70}, l_{72}, l_{78}, l_{82}, l_{83}, l_{84} are places from the model for the production of automotive gasolines (Chapter 2 of this dissertation) [160];

places l_{49}, l_{50}, l_{80}, l_{81} are places from the diesel fuel production model (Chapter 3 of this dissertation) [200];

places l_{26}, l_{42}, l_{77} are places from the model for the production of gaseous products (Chapter 4 of this dissertation) [202];

places l_{40}, l_{46}, l_{55}, l_{87}, l_{88}, l_{89} are places from the model for the production of heavy petroleum products (Chapter 5 of this dissertation) [223].

The processes in the oil refinery run in parallel. All fractions fractionated from the crude oil feed to the refinery in CDU-1, CDU-2, and VDU-2 (the so-called straight-run distillate fractions) are processed simultaneously in upgrading and conversion processes. In addition to the straight-run distillate fractions, the distillate fractions obtained in the conversion processes, FCC-PT, FCC, and H-Oil, are further upgraded or converted in the hydrotreating and catalytic cracking processes. This complex process, which consists of numerous sub-processes, is modeled by GN.

The processes of oil refining and the production of finished petroleum products are studied using the GN toolkit. It has been found that GNs, which can be viewed as extensions of Petri nets and whose definition is more complex than that of Petri nets and therefore allows the construction of a much more detailed model than any Petri net, can be used to model the parallel processes that occur in an oil refinery [224].

Knowledge of the relationships between various properties of crude oil, which are usually summarized in the oil analysis certificate, can reveal what might happen if a particular crude oil or blend of oils is processed in a refinery. This was the reason for examining 244 crude oil analysis certificates from around the world using inter-criteria analysis (ICrA). ICrA allows finding statistically significant relationships between multiple parameters that characterize a given complex object, while also determining the degree of similarity between the studied complex objects. Given that crude oil is a complex object characterized by a large number of criteria (oil properties), ICrA was initially applied to data from 22 samples of different crude oils, against 67 criteria (crude oil properties) [229]. In the present dissertation, the application of ICrA is extended to evaluate 244 crude oils by 151 properties. The purpose of the research in this chapter of the dissertation is to discuss the results of applying ICra to investigate the relationships between the overall petroleum physicochemical properties and those of the petroleum fraction properties of 244 crude oils and to determine the degree of similarity between these oil types

87 properties of the different oil fractions were also investigated. In addition, 28 properties of the oil fractions, related to the molecular weight of the fractions and the paraffinic, naphthenic and aromatic parts, were calculated using the correlations published in [230]. Thus, a total of 151 properties of the oil and its fractions of the 244 crude oils studied were processed by the intercriteria analysis..

The ICrA approach is specifically designed for data sets involving evaluations or measurements of multiple objects by multiple criteria. It is based on two concepts: intuitionistic fuzziness and indexed matrices. Intuitionistic fuzzy sets, defined by Atanassov [162], are one of the most popular and well-studied extensions of fuzzy sets, defined by Zadeh. In addition to the traditional membership function μA(x), defined for fuzzy sets to evaluate the membership of an element x to the set A with a real number in the interval [0;1], a second function, νA(x), has been introduced in intuitionistic fuzzy sets (IFS), determining the non-membership of an element x to the set A, which exists simultaneously with the membership function. Formally, the IFS itself is denoted by

$A = \{\langle x, \mu_A(x), \nu_A(x)\rangle \mid x \in E\}$,

and the following conditions apply:

$0 \leq \mu_A(x) \leq 1,\ 0 \leq \nu_A(x) \leq 1$,

$0 \leq \mu_A(x) + \nu_A(x) \leq 1$.

Many relations, operations, modal and topological operators on IFSs have been defined, which shows that IFSs are a non-trivial extension of the concept of fuzzy sets. The second concept on which the proposed method is based is the concept of the indexed matrix - a matrix to which two index sets have been added. The basics of the theory behind indexed matrices are described in [231] and have been further developed in [232].

Positive consonance values with μ = 0.75÷1.00 indicate a statistically significant positive relationship, with strong positive consonance showing values of μ = 0.95÷1.00, and weak positive consonance showing values of μ = 0.75÷0.85. Accordingly, negative consonance values with μ = 0.00÷0.25 indicate a statistically significant negative relationship, with strong negative consonance showing values μ = 0.00÷0.05, and weak negative consonance showing values μ = 0.15÷0.25. Dissonance has values μ = 0.33÷0.67 and indicates a lack of statistically significant relationship, with 0.33<μ < 0.5 indicating negative dissonance, and 0.5<μ < 0.67 - positive dissonance [229]. At the same time, function ν takes on the values 0.00÷ 0.25 (at μ = 0.75÷1.00), 0.00÷ 0.05 (at μ = 0.75÷1.00), 0.00÷ 0.75 (at μ = 0.00÷0.25), 0.00÷ 0.95, etc.

In this study, the analytical certificates of 244 crude oils from all parts of the world were processed. The grouping of the studied crude oils based on their API gravity is presented in Table 4. The range of variation of some important properties of the petroleum fractions of the studied crude oils is summarized in Table 5.

Table 4 Grouping of the studied 244 crude oils based on their API gravity

	API	Number of vrude oils	API range	SG (specific gravity) range
Condensates	>45	18	45.1 - 55.0	0.7587-0.8000
Extra light	40 - 45	31	40.1 - 44.7	0.8246-0.7993
Light	30 - 40	129	30.3 - 39.9	0.8255-0.8745
Medium	20 - 30	50	20.7 - 29.6	0.8783-0.9297
Heavy	10 - 20	16	10.1 - 20.0	0.934-0.9993

The data for the 244 crude oils, characterized by 151 properties, were processed using ICrA and a matrix of consonance and dissonance values between all the studied raw oils was obtained. The strongest consonance for a pair of oils was recorded at $\mu = 0.983$, while the strongest dissonance was obtained at $\mu = 0.56$. This means that some of the studied crude oils have very close values of their properties, while others are completely different. Table 6 shows the proximity between the properties of the pair of crude oils that received the highest consonance value for each of the groups of raw materials classified based on the density of the raw material. It is interesting to note that the consonance values are lower when only the relative density and the fraction yields determined by distillation at true boiling points are used in the evaluation process using ICrA analysis (Table 7).

This observation suggests that these crude oil properties could not fully describe the possible variations of the variety of combinations among the millions of chemical compounds present in the oil. Therefore, the greater the number of crude oil properties included in the ICrA analysis, the higher the degree of similarity between the studied oils can be found.

Due to the extremely high complexity and variety of combinations among the millions of chemical compounds contained in the oil, it is very difficult or even impossible to find strong statistically significant relationships between the properties of the crude oil and the properties of the oil fractions. However, the use of a mathematical tool such as inter-criteria analysis can allow the finding of feedstocks whose properties are very similar. In this way, based on previous experience in oil refining, a selection of potentially profitable new feedstocks for processing in the refinery can be made.

Table 5 Range of variation of some fraction properties of the studied 244 crude oils

Properties		C_5 - 70°C	70 – 100°C	100 - 150°C	150-190°C	190-235°C	235-280°C	280-343°C	343-565°C	343°C+	565°C+
SG	min	0.6358	0.6779	0.7298	0.7524	0.7700	0.7886	0.8049	0.8383	0.8451	0.8775
	max	0.7230	0.7577	0.8009	0.8293	0.8612	0.8899	0.9202	0.9721	1.0272	1.0938
RON	min	52.0	37.8	20.6	10.9						
	max	87.7	77.5	72.3	74.1						
Naphthenes, vol%	min		9.7	22.2	26.7						
	max		20.5	24.8	27.4						
Aromatics, vol.%	min		7.7	14.5	16.3	17.8	20.2				
	max		22.4	29.1	34.4	42.1	50.7				
2A+N	min			51.2	59.4						
	max			83.0	96.2						
Freezing Point, °C	min					-85.7	-62.58				
	max					-28.1	-2.39				
Cetane Index	min					28.15	33.99	35.54			
	max					64.05	69.05	70.98			
Smoke point, mm	min					12.30	7.00				
	max					43.83	39.44				
Pour Point, °C	min							-67.61	-23.15		
	max							17.63	64.42		
CCR, wt. %	min								0.02	0.02	1.70
	max								6.25	19.00	38.02
Ni, ppm	min								0.01	0.09	1.00
	max								12.79	210.05	717.40
V, ppm	min								0.001	0.06	0.09
	max								19.48	1406	2746
VIS at 100 °C, mm^2/s	min								3.11	1.70	18.2
	max								20.61	1750.00	1.10^6

Table 6 The highest consonance of crude pairs from the five studied crude groups and some of the properties used for ICrA evaluation

Consonanse	μ = 0.966; υ = 0.03		μ = 0.974; υ = 0.02		μ = 0.983; υ = 0.01		μ = 0.963; υ = 0.035		μ = 0.974; υ = 0.026	
Properties/Crude	KAKAP	TAPIS BLEND	BREGA	ZUEITINA	NIKISKI TERMINAL	DRIFT RIVER	FATEH	IRANIAN HEAVY	WILLMINGTON	BACHAQUERO
C_5/70_SG	0.6529	0.6560	0.6572	0.6532	0.6486	0.6509	0.6545	0.6533	0.6645	0.6675
C_5/70_RON	74.2	72.7	68.3	69.3	72.9	73.6	69.9	71.3	82.8	73.6
70/100_SG	0.713	0.706	0.723	0.720	0.717	0.716	0.714	0.703	0.727	0.733
70/100_Aro	7.7	3.4	2.6	4.5	3.9	2.9	7.8	9.1	1.3	4.7
70/100_RON	56.3	62.0	59.9	60.6	66.3	67.5	57.1	59.8	66.0	69.3
100/150_SG	0.746	0.756	0.751	0.747	0.758	0.757	0.752	0.746	0.767	0.777
100/150_2A+N	47.8	44.5	55.4	46.6	68.6	69.5	61.2	67.3	84.7	85.0
100/150_RON	44.0	49.4	45.0	40.6	53.0	57.0	47.1	46.6	62.1	63.9
190/235_SG	0.781	0.795	0.804	0.803	0.817	0.819	0.811	0.809	0.840	0.836
190/235_Aro	16.5	12.8	15.5	14.4	16.0	15.8	23.0	23.4	15.1	20.4
190/235_VIS	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8
235/280_SG	0.803	0.822	0.823	0.825	0.840	0.841	0.843	0.835	0.871	0.865
235/280_Aro	14.9	14.9	19.0	13.7	12.6	12.1	30.5	36.8	13.4	34.0
235/280_CI	62.7	54.7	54.4	53.9	48.5	47.9	47.5	50.2	38.9	40.6
235/280_VIS	1.0	1.1	1.0	1.0	1.1	1.1	1.1	1.0	1.2	1.1
343/565_SG	0.857	0.866	0.888	0.884	0.916	0.917	0.926	0.924	0.962	0.953
343/565_Kw	12.57	12.39	12.25	12.29	11.86	11.84	11.77	11.80	11.39	11.46
343/565_VIS	3.3	3.9	6.1	6.4	7.8	7.9	8.1	7.4	11.5	14.5
343°C+_SG	0.866	0.885	0.912	0.908	0.947	0.946	0.951	0.972	0.997	1.001
343°C+_CCR	1.60	2.00	4.10	4.10	6.50	7.95	6.59	10.00	11.20	14.20
343°C+_VIS	4.10	5.98	14.00	13.10	21.10	25.30	22.10	45.00	309	247

Table 7 Consonance of the crude pairs from the five studied crude groups evaluated only on the base of the bulk properties: specific gravity, sulphur and TBP yields

Consonance	$\mu = 0.910$; $\upsilon = 0.09$		$\mu = 0.910$; $\upsilon = 0.09$		$\mu = 0.923$; $\upsilon = 0.08$		$\mu = 0.923$; $\upsilon = 0.08$		$\mu = 0.897$; $\upsilon = 0.103$	
Properties /Crude	KAKAP	TAPIS BLEND	BREGA	ZUEITINA	NIKISKI TERMINAL	DRIFT RIVER	FATEH	IRANIAN HEAVY	WILLMINGTON	BACHAQUERO
Crude SG	0.7732	0.7976	0.8232	0.8189	0.8519	0.8483	0.8705	0.8713	0.9427	0.9541
Crude Sulphur, %	0.05	0.03	0.21	0.28	0.10	0.09	2.00	1.73	1.59	2.40
TBP yields										
Gas C_3-C_4, wt.%	2.35	1.34	1.58	2.00	1.42	1.54	1.24	1.50	0.38	0.41
C_5-70°C, wt.%	6.96	5.57	5.16	5.27	3.84	3.83	2.42	3.64	0.72	0.98
70-100°C, wt.%	7.39	5.19	5.25	4.63	4.58	5.68	4.39	3.73	1.31	1.23
100-150°C, wt.%	15.17	12.49	9.64	10.68	8.39	9.90	7.67	7.08	3.18	2.37
150-190 °C, wt.%	12.33	10.66	7.87	8.38	7.16	7.68	6.35	6.38	3.50	2.29
190-235°C, wt.%	11.54	12.70	8.93	9.73	8.40	8.28	7.52	7.29	5.97	3.52
235-280°C, wt.%	12.07	12.91	8.98	8.76	8.55	8.47	7.82	7.31	6.45	4.91
280-343°C, wt.%	13.24	14.49	11.59	12.36	11.92	11.96	11.49	10.27	9.86	10.38
343-565°C, wt.%	17.05	21.15	29.96	28.44	33.15	31.35	34.89	30.09	41.13	37.47
565+°C, wt.%	1.88	3.50	11.04	9.72	12.54	11.32	16.18	22.69	27.50	36.40

A GN model of the crude oil selection process

The present GN has 7 transitions, 18 places and 15 types tokens (see Fig. 26).

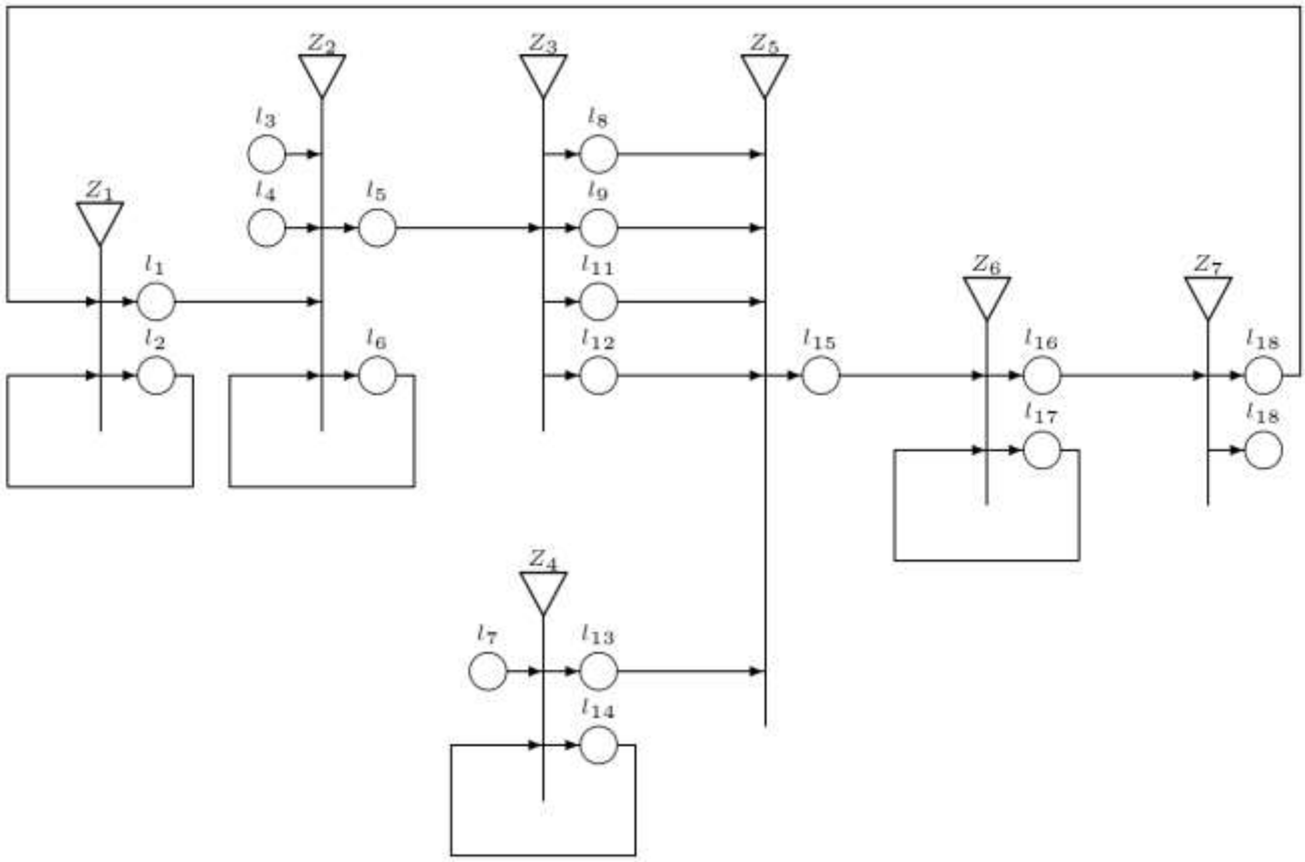

Fig. 26: GN model of crude oil selection process of a petroleum refinery

Initially, in the GN there are three tokens:

* token δ_1 with initial and current characteristic

"full analysis of crude oils processed and to be processed in the refinery,

* token δ_2 with initial and current characteristic

"market information about available crude oils, their volumes and their qualities",

* token ι with initial and current characteristic

"program product for realization of the ICrA".

The GN-transitions are the following.

$$Z_1 = \langle \{l_2, l_{17}\}, \{l_1, l_2\}, r_1 \rangle,$$

where

$$r_1 = \begin{array}{c|cc} & l_1 & l_2 \\ \hline l_2 & W_{2,1} & true \\ l_{17} & false & true \end{array},$$

where

$W_{2,1}$ = «there are tokens in positions l_3 and l_4».

Token ζ_1 from place l_{17} enters place l_2 and unites with token δ_1. The current characteristic of token δ_1 is actualized with the information from the characteristic of token ζ_1.
Token δ_1 splits to two tokens - the same token δ1 that continues to stay in place l_2 and token η that enters place l_1 with characteristic "refinery operation data, refinery performance evaluation".
On some time-stept an α-token enters place l_3 with a characteristic "refinery operation data".
On some time-stept a β-token enters place l_4 with a characteristic "refinery performance evaluation".

$$Z_2 = \langle \{l_1, l_3, l4, l_6\}, \{l_5, l_6\}, r_2 \rangle,$$

where

$$r_2 = \begin{array}{c|cc} & l_5 & l_6 \\ \hline l_1 & false & true \\ l_3 & false & true \\ l_4 & false & true \\ l_6 & true & false \end{array} .$$

Tokens α, β and η enter place l_6 and unite in one token γ with initial characteristic

"classification of the crude oils to be processed in the oil refinery in groups".

In the next time-step, token γ enters place l_5 without a new characteristic.

$$Z_3 = \langle \{l_5\}, \{l_8, l_9, l_{10}, l_{11}\}, r_3 \rangle,$$

where

$$r_3 = \begin{array}{c|cccc} & l_8 & l_9 & l_{10} & l_{11} \\ \hline l_5 & true & true & true & true \end{array} .$$

Token γ splits to four tokens γ_1, γ_2, γ_3, γ_4 that obtain the following characteristics:

token $\gamma 1$ (in place l_8)

"list of the crude oils of Group 1 (crude oil which can be processed without any limitations)",

token γ_2 (in place l_9)

"list of the crude oils of Group 2 (crude oils, which can be processes at limited capacity of refinery)",

token γ_3 (in place l_{10})

"list of the crude oils of Group 3 (crude oils, which can be processed only in blends in appropriate concentration)",

token γ_4 (in place l_{11})

“list of the crude oils of Group 4 (Crude oils, which cannot be processed)”.

On some time-step t a μ-token enters place l_7 with a characteristic

“Up-to-date information on the current state of crude oil markets around the world”.

$$Z_4 = \langle \{l_7, l_{13}\}, \{l_{12}, l_{13}\}, r_4 \rangle,$$

where

$$r_4 = \begin{array}{c|cc} & l_{12} & l_{13} \\ \hline l_{13} & W_{13,12} & true \\ l_{18} & false & true \end{array},$$

where

$W_{13,12}$ = «There are token in positions l_8, l_9, l_{10} and l_{11}».

Each one of the μ-tokens from place l_7 enters place l_{13} and unites with token δ_2. The current characteristic of token δ_2 is actualized with the information from the characteristic of the current token μ.

Token δ_2 splits to two tokens - the same token δ_2 that continues to stay in place l_{13} and token ε that enters place l_{12} with characteristic

“list of the existing crude oils in the refinery”.

$$Z_5 = \langle \{l_7, l_8, l_9, l_{11}, l_{12}\}, \{l_{14}\}, r_5 \rangle,$$

where

$$r_5 = \begin{array}{c|c} & l_{14} \\ \hline l_7 & true \\ l_8 & true \\ l_9 & true \\ l_{11} & true \\ l_{12} & true \end{array}.$$

The tokens γ_1, γ_2, γ_3, γ_4 and η enter place l_{14} and unite in one token – γ with the characteristic

“Data for the ICrA”.

$$Z_6 = \langle \{l_{14}, l_{16}\}, \{l_{15}, l_{16}\}, r_6 \rangle,$$

where

$$r_6 = \begin{array}{c|cc} & l_{15} & l_{16} \\ \hline l_{14} & false & true \\ l_{16} & true & false \end{array}.$$

Token γ from place l_{14} enters place l_{16} and unites with token ι. The latest token obtains the new characteristic “initial parameters for ICrA computing”.

In the next time-step, token ι splits to two tokens - the same token ι that continues to stay in place l_{16} and token γ that enters place l_{15} with the characteristic

“list of the most suitable for processing crude oils”.

$$Z_7 = \langle \{l_{15}\}, \{l_{17}, l_{18}\}, r_7 \rangle,$$

where

$$r_7 = \begin{array}{c|ccc} & l_{17} & l_{18} & l_{18} \\ \hline l_{15} & true & true & true \end{array}.$$

Token γ splits to two tokens ζ and γ that obtain the following characteristics:

tokens ζ (in place l_{17}):

“information that is returned in the full analysis of crude oils processed and to be processed in the refinery”,

and token γ (in place l_{18})

“Decision on the optimal basket of crude oils for processing in the refinery and purchasing decision”.

This study demonstrated that the crude oil selection process, which is implemented through ICrA, can be modeled by the GN toolkit. The software implementation of this GN model, together with the software implementation of ICrA that is already available, can help refineries around the world optimize their crude oil selection process. This issue is particularly relevant in the current dynamics of oil markets, and resolving it can ensure the sustainability of oil refineries, thereby increasing their efficiency.

Publications for Chapter 6

The presented results are included in the article:

224. Stratiev, D.; Shishkova, I.; Angelova, N.; Stratiev, D.D.; Atanassov, K. Generalized Net Model of the Processes in a Petroleum Refinery—Part I: Theoretical Study. Mathematics 2024, 12, 3017.

239.Stratiev, D.D.; Stratiev, D.; Hadjiivanov, K.; Atanassov, K. Generalized net model of the crude oil selection process in an oil refinery. Comptes rendus de l’Acad´emie bulgare des Sciences 2025, Tome 78, No 12, 1871─1878.

CONCLUSION-SUMMARY OF THE OBTAINED RESULTS

The main conclusions of this dissertation are summarized as follows:

1. A GN-model has been developed that describes the processes of production of different brands of automotive gasolines in an oil refinery. It can be used to synchronize and optimize these processes in a real system for process control and automation. The functioning of the GN-model has been simulated in an environment for developing generalized nets.

2. A GN-model has been developed that describes the processes of production of different classes of diesel fuels in an oil refinery, taking into account the available quantities of the various components of the diesel fuel. It can be used to synchronize and optimize these processes in a real system for process control and automation.

3. The process of producing gaseous products in an oil refinery, such as fuel gas, propane-butane and propylene, which can be exported as a final finished product or used as a raw material for the production of polypropylene, is a complex parallel process that is difficult to model using linear and even dynamic programming. The difficulty comes from the inability to reflect the logic of the cause-and-effect relationships in it, which are easily interpreted through predicates for transient conditions. A visual tool for representing real processes are UML diagrams, which have been shown to be able to be represented using GN. In this dissertation, a GN model has been developeed for the production of fuel gas, propane-butane, propylene and polypropylene in an oil refinery.

4. Similar to the modeling of the production processes of various grades of automotive gasoline, automotive diesel fuel and fuel gas, propane-butane, propylene and polypropylene, the production processes of various grades of heavy petroleum products in an oil refinery can also be modeled using generalized networks. All these processes are complex and parallel, and their modeling using GN allows one to avoid the shortcomings of linear and even dynamic programming (where the difficulty comes from the inability to reflect the logic of cause-and-effect relationships). The combination of the four already developed separate GN models, which simulate in detail the production processes of all petroleum products, can be used as submodels of a higher hierarchical GN model.

5. A highly hierarchical GN model of a modern oil refinery has been developed, which models all petroleum product production processes.

6. Due to the extremely high complexity and variety of combinations between the myriad organic compounds that make up an oil, it is very difficult or even impossible to find strong statistically significant relationships between the properties of crude oil and the properties of its fractions. However, the use of a mathematical tool such as inter-criteria analysis can allow finding crude oils whose properties are very similar. In this way, based on previous experience in oil refining, a selection of potentially profitable new crude oils for processing in the oil refinery can be made.

7. A GN model of the crude oil selection process in an oil refinery has been developed.

SCIENTIFIC CONTRIBUTIONS AND SCIENTIFIC-APPLICATION CONTRIBUTIONS

1. For the first time, a GN model has been developed for the production of automotive gasolines in a modern oil refinery.

2. For the first time, a GN model has been developed for the production of automotive diesel fuels in a modern oil refinery.

3. For the first time, a GN model has been developed for the production of gas products (fuel gas, propane-butane, propylene) and polypropylene in a modern oil refinery.

4. For the first time, a GN model has been developed for the production of all oil products in a modern oil refinery.

5. A GN model of the crude oil selection process in an oil refinery has been developed, which includes an inter-criteria analysis, allowing the selection of a suitable crude oil to be carried out by applying this GN model and using historical information on the processing of different types of crude oil in a modern oil refinery.

LIST OF PUBLICATIONS ON THE DISSERTATION:

1. **Danail Stratiev**, Dafina Zoteva, Dicho Stratiev & Krassimir Atanassov. (2022). Modelling the Process of Production of Automotive Gasoline by the Use of Generalized Nets, In: , et al. Uncertainty and Imprecision in Decision Making and Decision Support: New Advances, Challenges, and Perspectives. IWIFSGN BOS/SOR 2020 2020. Lecture Notes in Networks and Systems, vol 338. Springer, Cham. https://doi.org/10.1007/978-3-030-95929-6_27.(Scopus Q4, SJR = 0.170).
2. **Danail Stratiev**, Dicho Stratiev, Krassimir Atanassov, "Modelling the Process of Production of Diesel Fuels by the Use of Generalized Nets", Mathematics 2021, 9, 2351. (Web of Science Q1, IF= 2.258).
3. **Danail Stratiev**; Angel Dimitriev; Dicho Stratiev; Krassimir Atanassov. Modeling the Production Process of Fuel Gas, LPG, Propylene, and Polypropylene in a Petroleum Refinery Using Generalized Nets. Mathematics 2023, 11, 3800. https://doi.org/10.3390/math11173800 (Web of Science Q1, IF= 2.4).
4. **Danail Stratiev**; Angel Dimitriev; Dicho Stratiev; Krassimir Atanassov. Generalized Net Model of Heavy Oil Products' Manufacturing in Petroleum Refinery. Mathematics 2023, 11, 4753. https://doi.org/10.3390/math11234753. (Web of Science Q1, IF= 2.4).
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Danail Stratiev, Dafina Zoteva, Dicho Stratiev & Krassimir Atanassov. (2022). Modelling the Process of Production of Automotive Gasoline by the Use of Generalized Nets, In: , et al. Uncertainty and Imprecision in Decision Making and Decision Support: New Advances, Challenges, and Perspectives. IWIFSGN BOS/SOR 2020 2020. Lecture Notes in Networks and Systems, vol 338. Springer, Cham. https://doi.org/10.1007/978-3-030-95929-6_27.(Scopus Q4, SJR = 0.170).

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